AEDC-TDR-63-190

# MOLLIER DIAGRAM FOR AIR



By

Wanda J. Little
von Kármán Gas Dynamics Facility
ARO, Inc.

TECHNICAL DOCUMENTARY REPORT NO. AEDC-TDR-63-190

September 1963

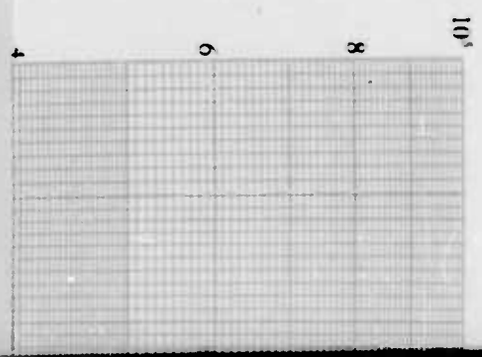
Program Element 61405014/8951, Task 89603

(Prepared under Contract No. AF 40(600)-1000 by ARO, Inc., contract operator of AEDC, Arnold Air Force Station, Tenn.)

ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

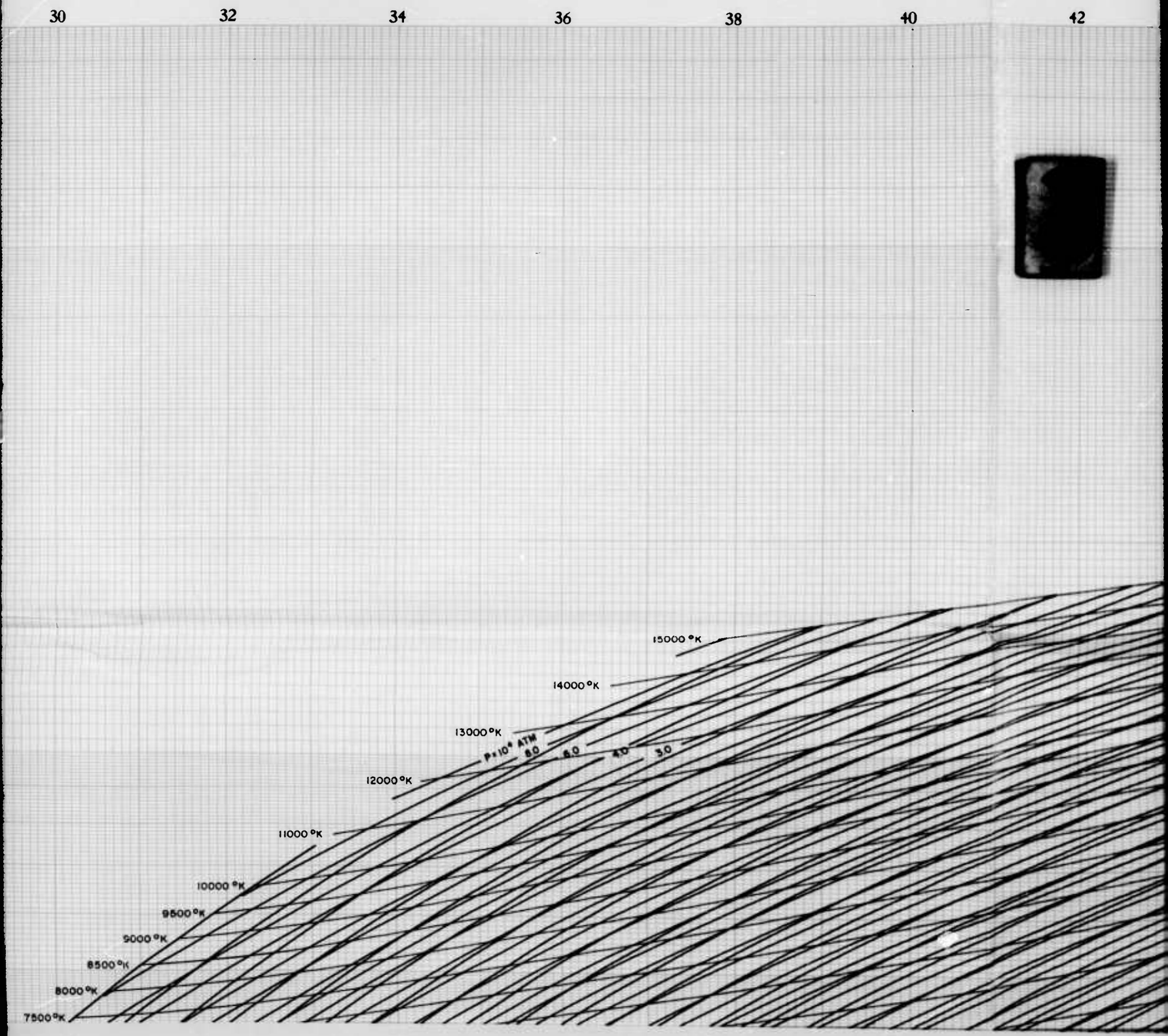


# MOLLIER DIAGRAM FOR EQUILIBRIUM AIR
## ARO, INC. MARCH 1964



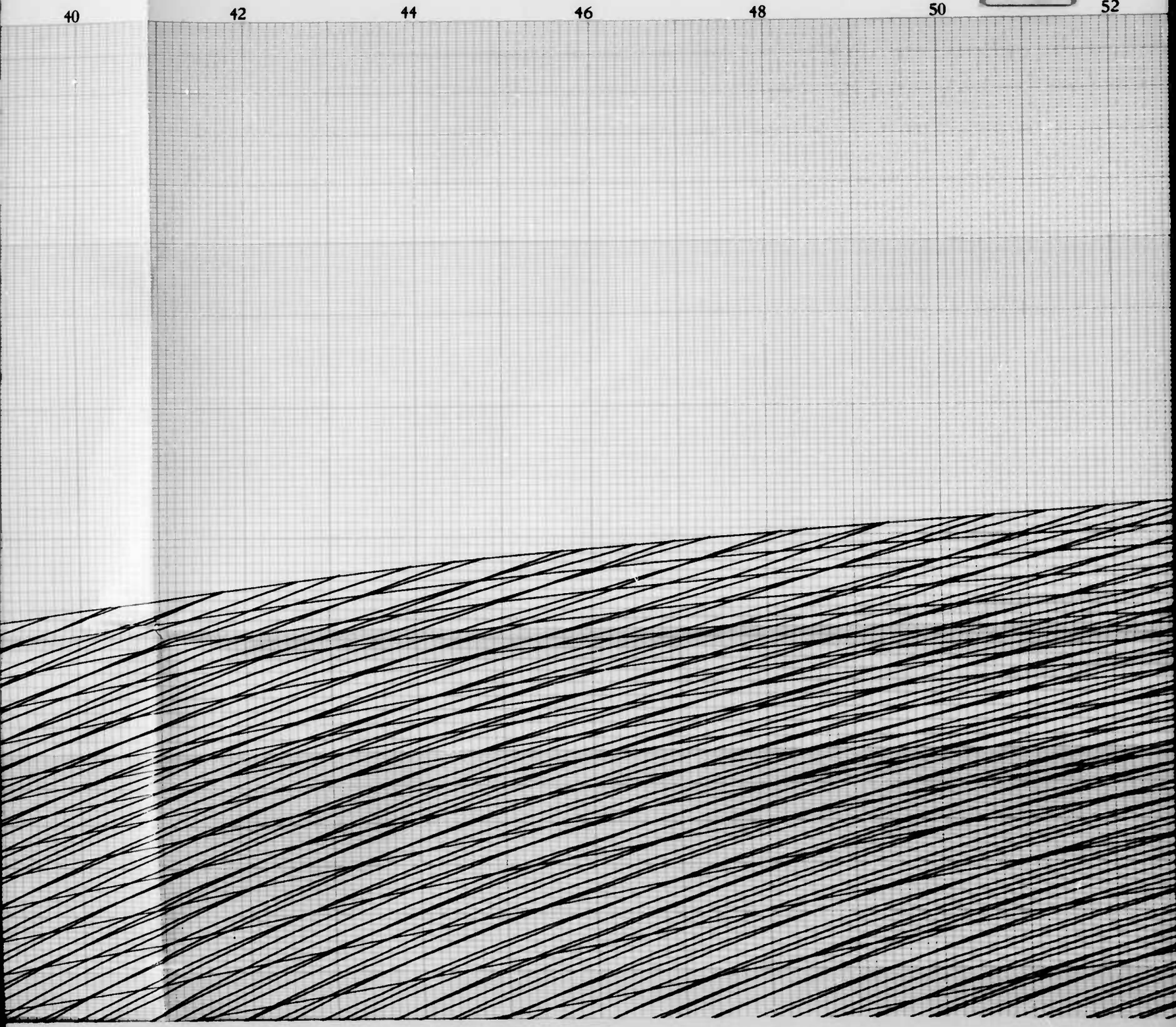
# MO

# MOLLIER DIAGRAM FOR EQ



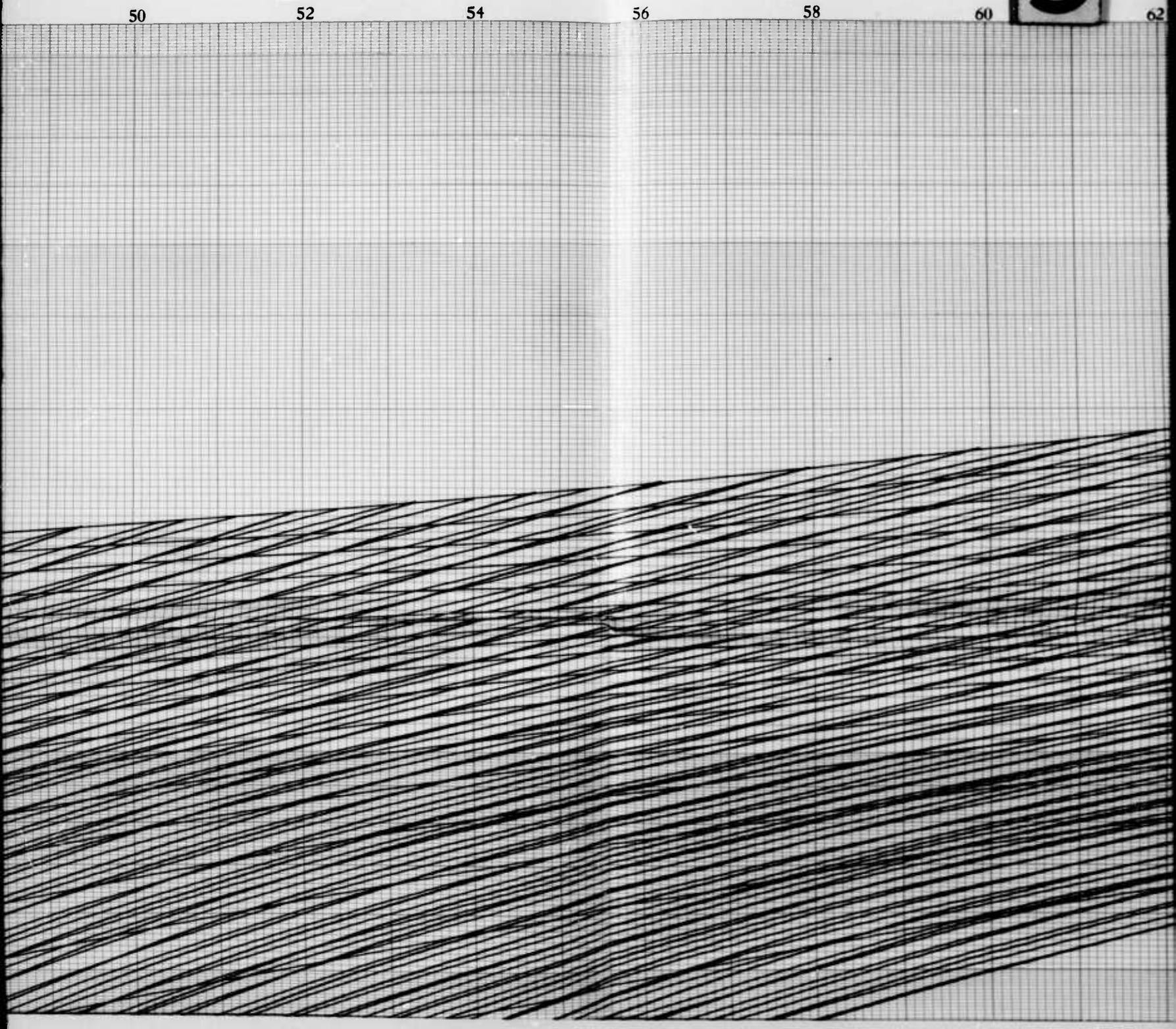
# M FOR EQUILIBRIUM AIR

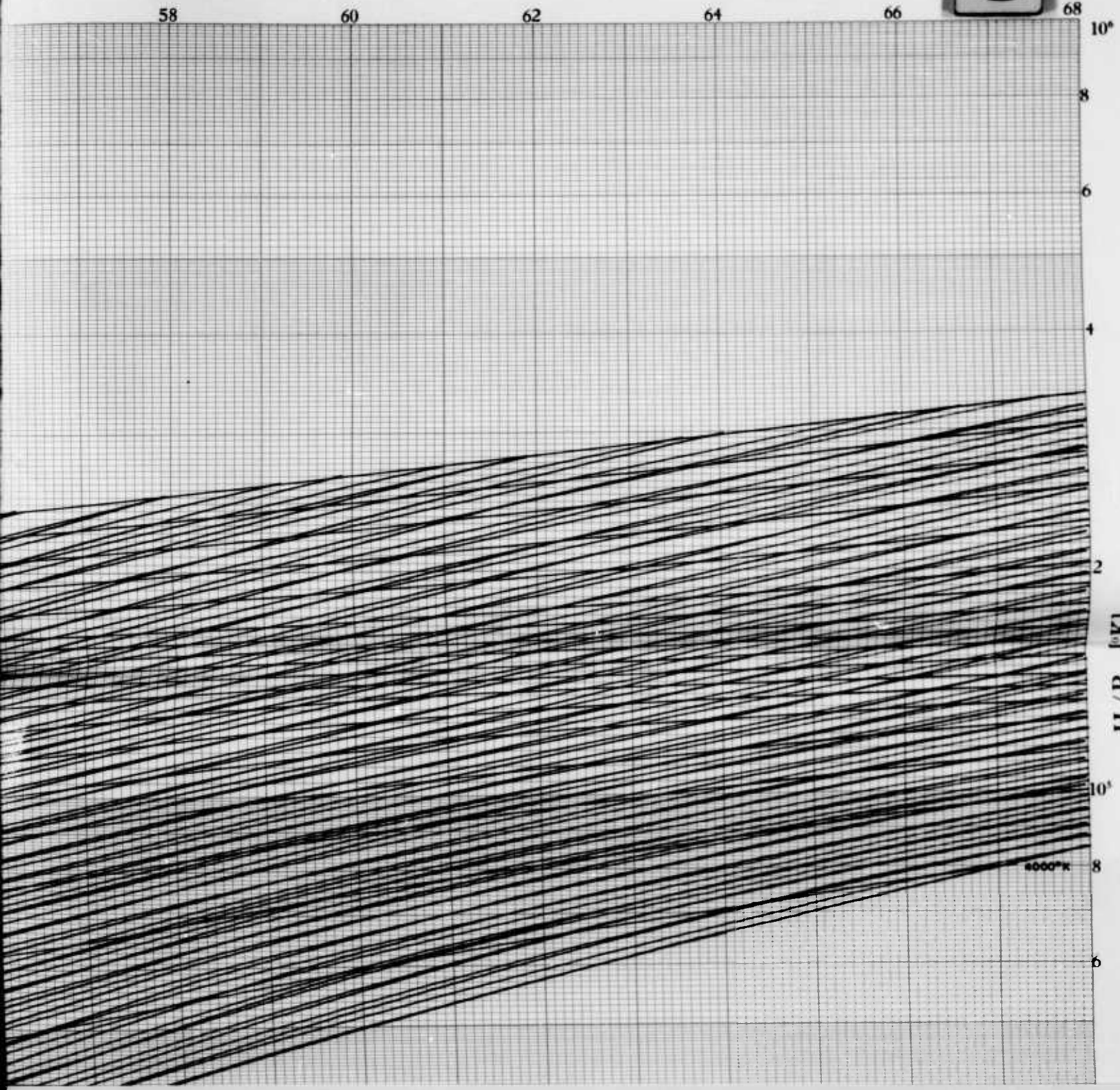
4



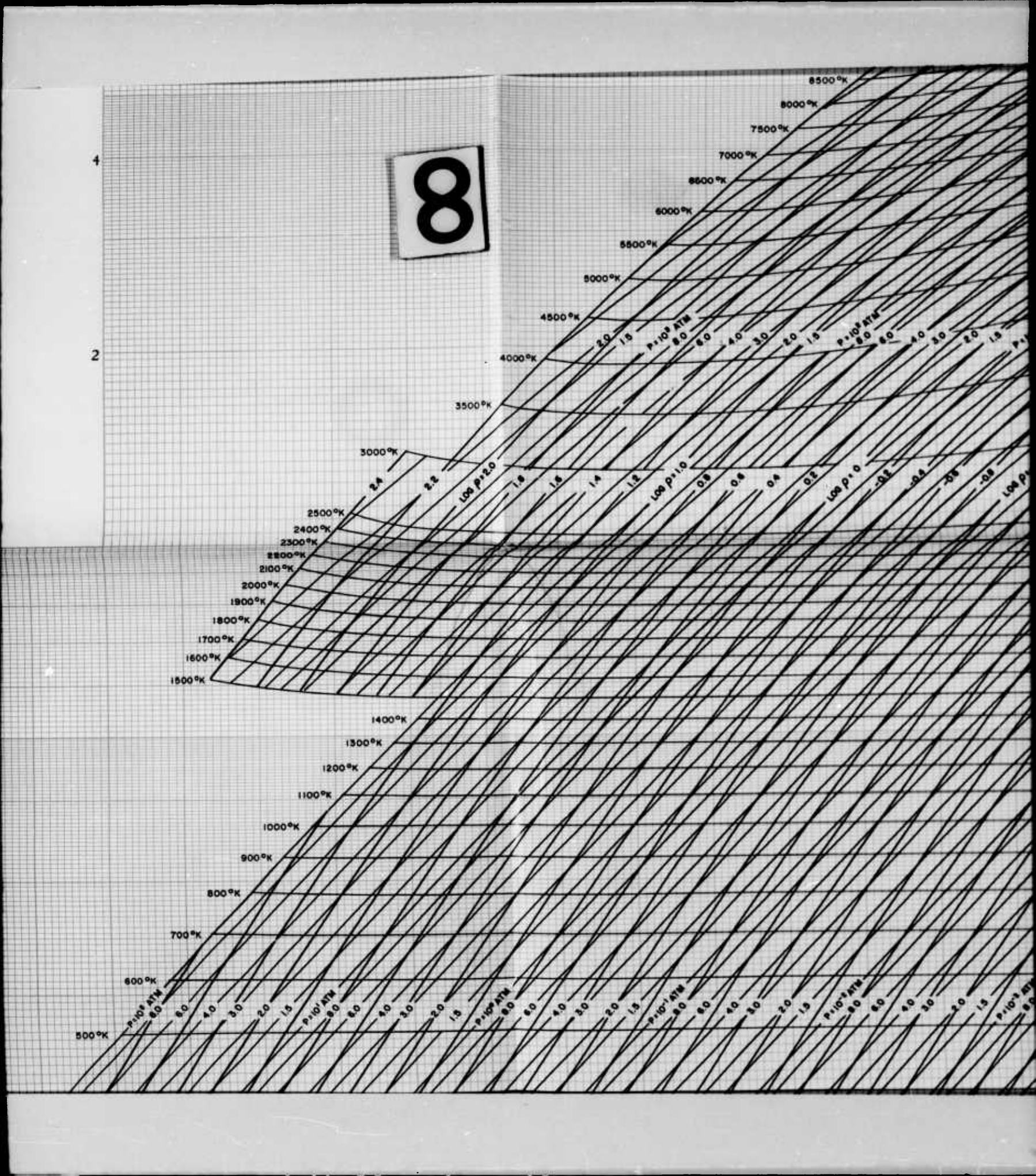
R

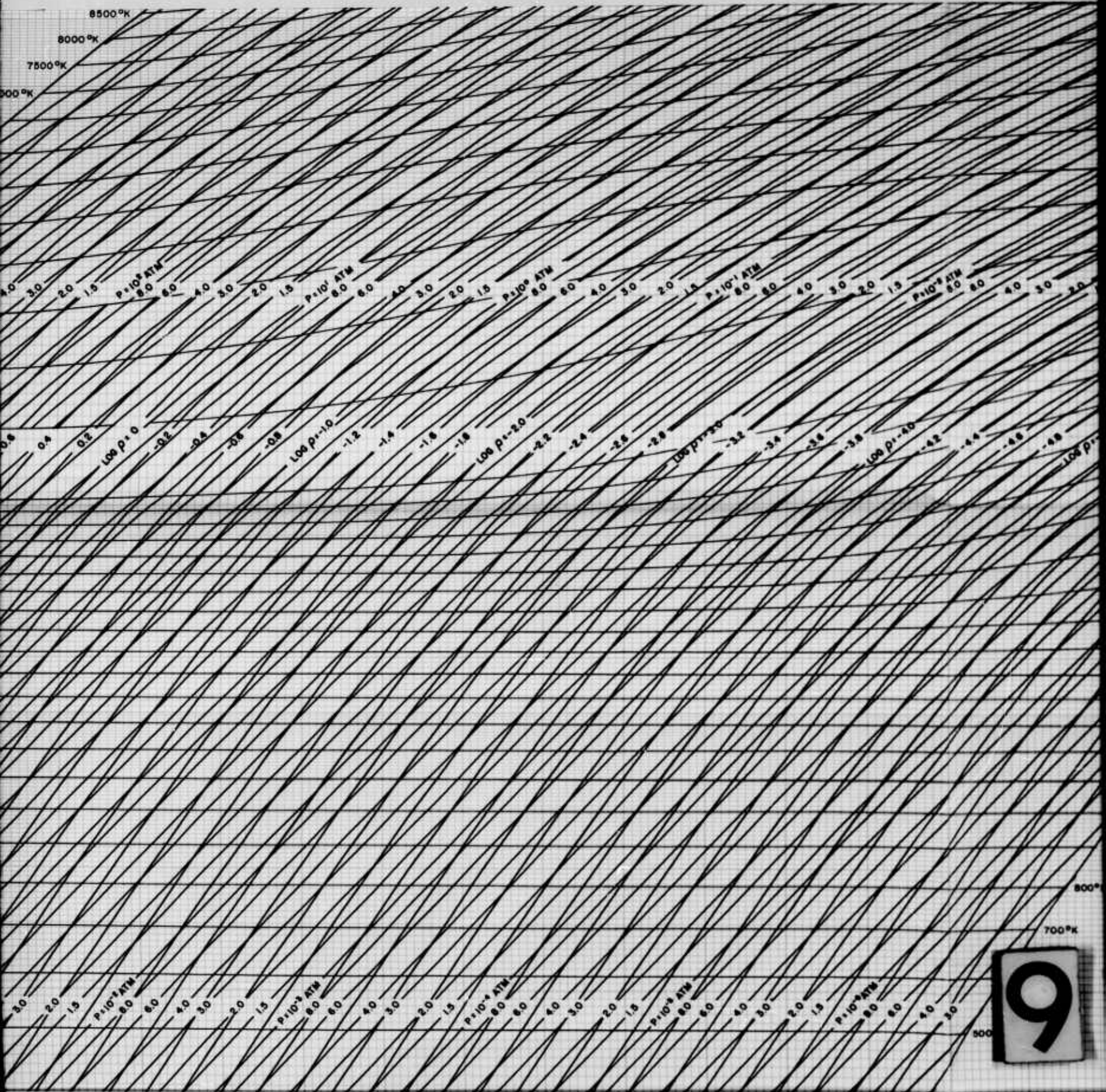
5

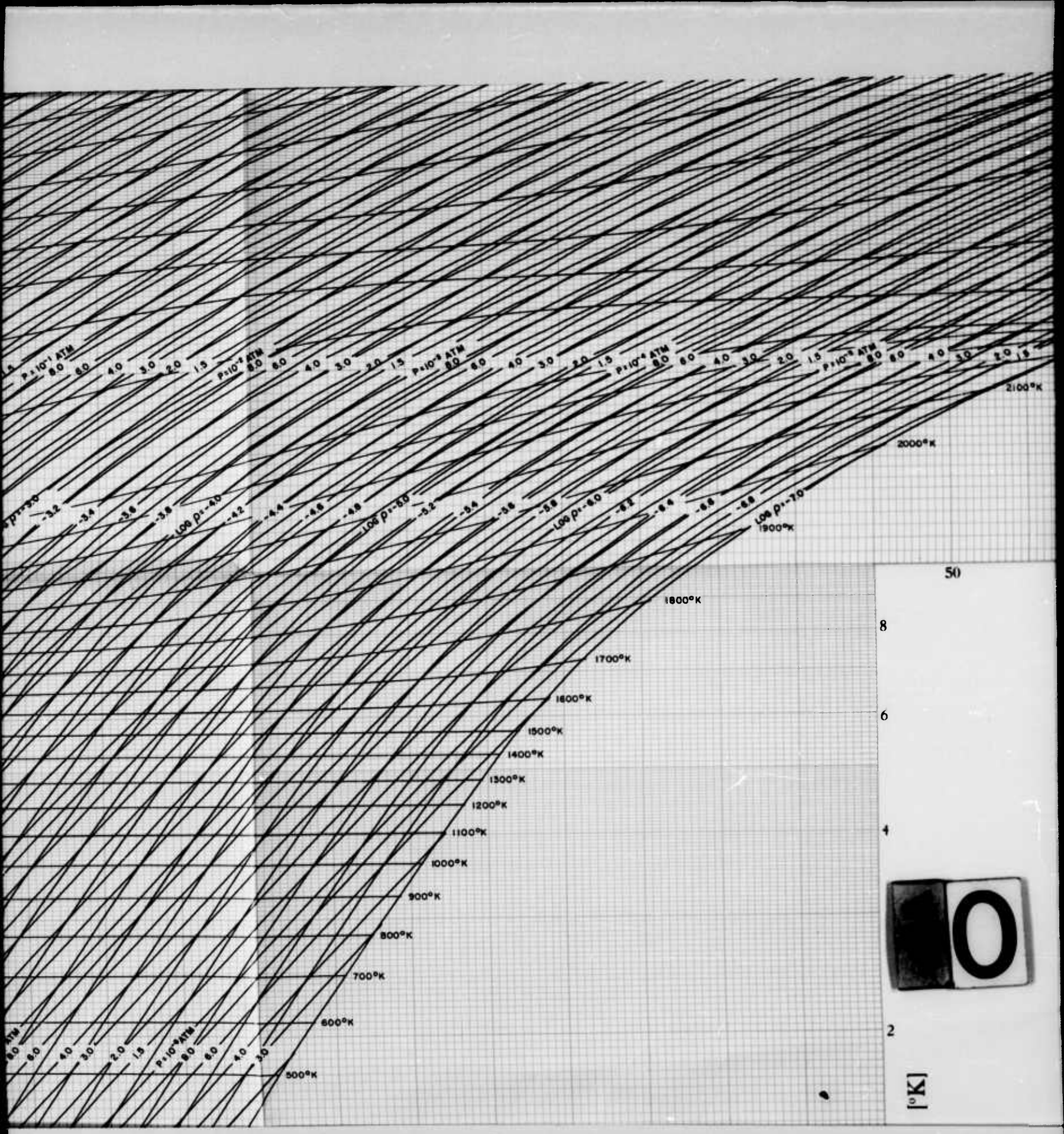


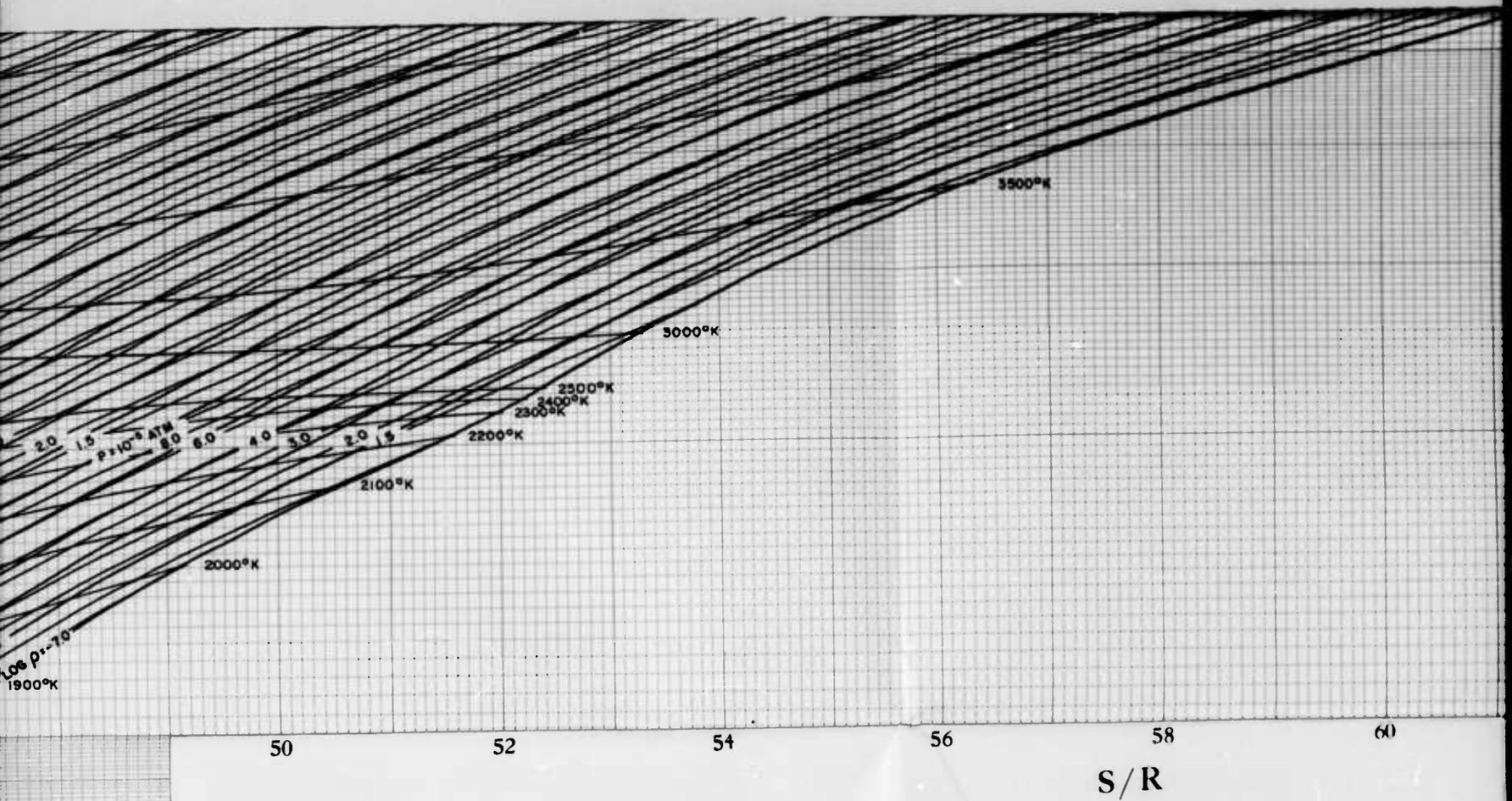

58
60
62
64
66
68
10⁶
8
6
4
2
10⁵
8
6
4000°K
H/R [°K]


7
4
2
10⁴
8
6
4
2
/R [°K]
2400
2300
2200°K
2100°K
2000°K
1900°K
1800°K
1700°K
1600°K
1500°K
1100
1000°K
900°K
800°K
700°K
600°K
500°K
400°K
P=10⁸ ATM
8.0
6.0
4.0
3.0
2.0
1.5
P=10⁷


8
8500°K
8000°K
7500°K
7000°K
6500°K
6000°K
5500°K
5000°K
4500°K
4000°K
3500°K
3000°K
2500°K
2400°K
2300°K
2200°K
2100°K
2000°K
1900°K
1800°K
1700°K
1600°K
1500°K
1400°K
1300°K
1200°K
1100°K
1000°K
900°K
800°K
700°K
600°K
500°K
P=10⁴ ATM
P=10³ ATM
P=10² ATM
P=10¹ ATM
P=10⁰ ATM
P=10⁻¹ ATM
P=10⁻² ATM
P=10⁻³ ATM
LOG p=2.0
LOG p=1.0
LOG p=0
LOG p=
8.0
6.0
4.0
3.0
2.0
1.5
2.4
2.2
1.8
1.6
1.4
1.2
0.8
0.6
0.4
0.2
-0.2
-0.4
-0.6
-0.8
4
2


8500°K
8000°K
7500°K
700°K
P=10² ATM
P=10¹ ATM
P=10⁰ ATM
P=10⁻¹ ATM
P=10⁻² ATM
P=10⁻³ ATM
P=10⁻⁴ ATM
LOG ρ=-1.0
LOG ρ=-2.0
LOG ρ=-3.0
LOG ρ=-4.0
9

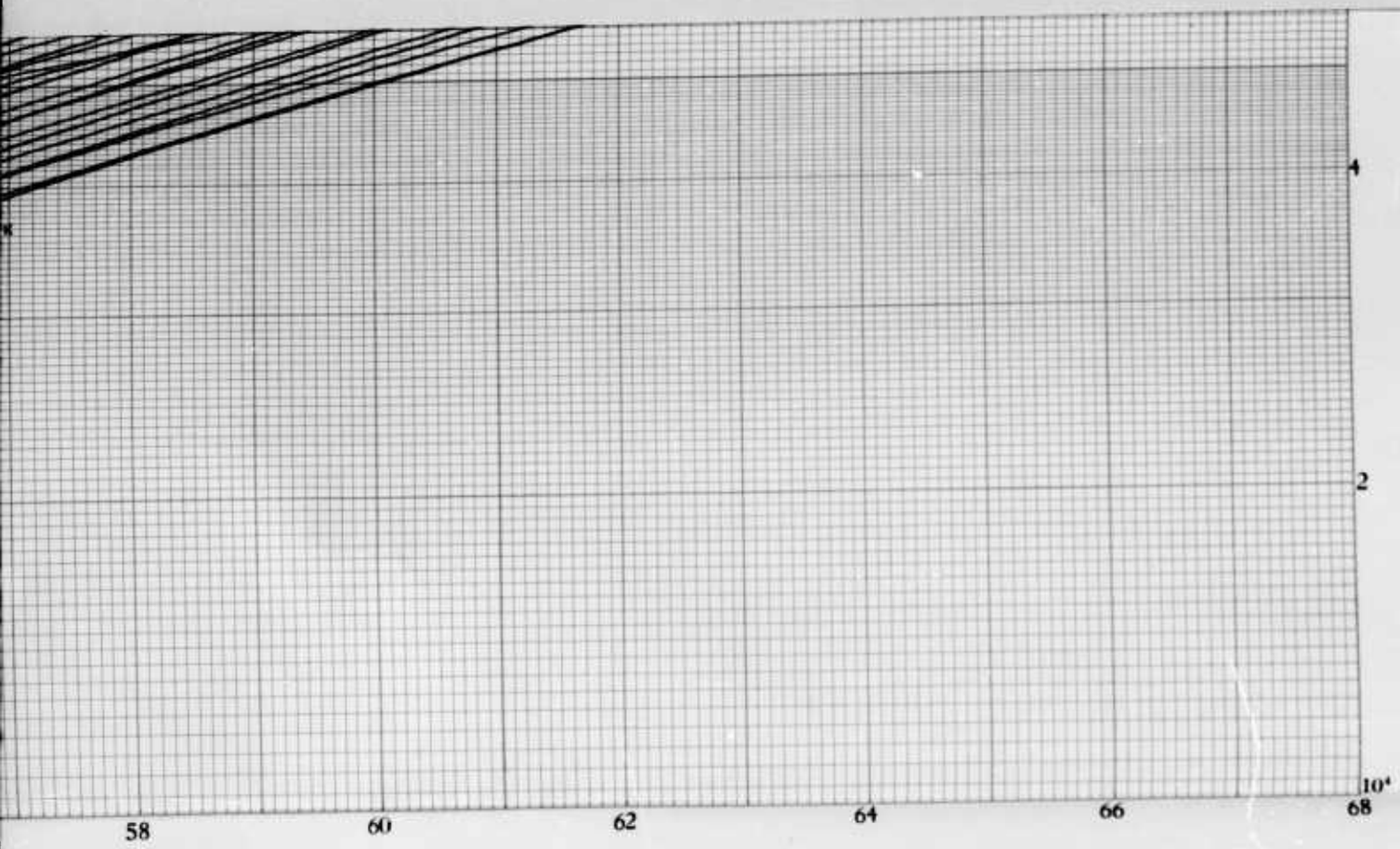

P=10⁻¹ ATM
P=10⁻² ATM
P=10⁻³ ATM
P=10⁻⁴ ATM
P=10⁻⁵ ATM
P=10⁻⁶ ATM
8.0
6.0
4.0
3.0
2.0
1.5
LOG ρ=-3.0
LOG ρ=-4.0
LOG ρ=-5.0
LOG ρ=-6.0
LOG ρ=-7.0
2100°K
2000°K
1900°K
1800°K
1700°K
1600°K
1500°K
1400°K
1300°K
1200°K
1100°K
1000°K
900°K
800°K
700°K
600°K
500°K
50
8
6
4
2
[°K]




# MOLLIER DIAGRAM FOR EQUILIBRIU

PREPARED BY THE STAFF OF VON KARMAN GAS DYNAMIC
FACILITY, ARO, INC., CONTRACT OPERATORS OF ARNOLD E
GINEERING DEVELOPMENT CENTER, UNITED STATES A
FORCE, ARNOLD AIR FORCE STATION, TENNESSEE. PRINTED
THE PARTHENON PRESS, NASHVILLE, TENNESSEE, MARCH 19

This chart is a composite of sectional parts given by Wanda J. Little, "
Air," AEDC-TDR-63-190, September 1963. The data for it are derived

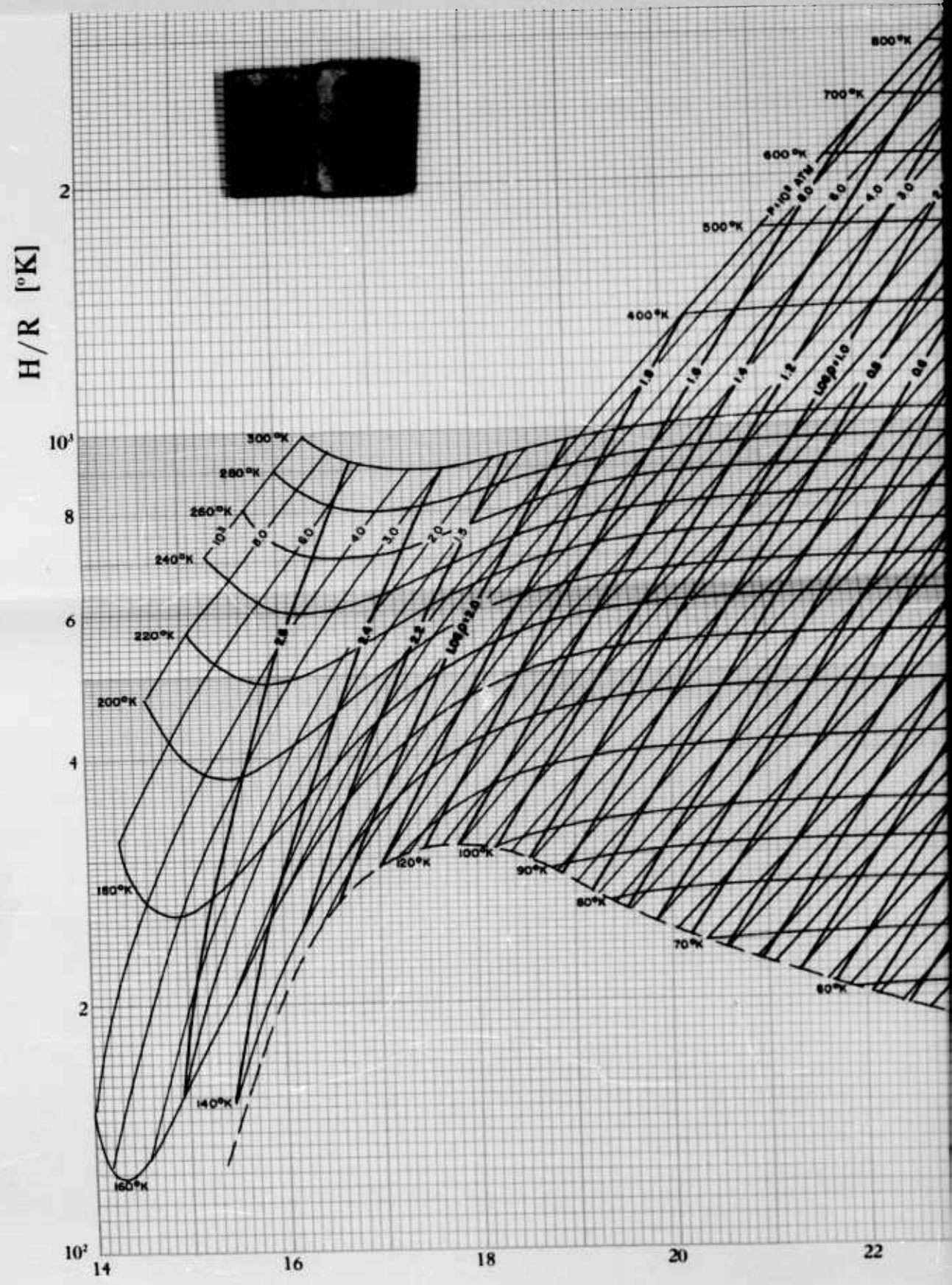


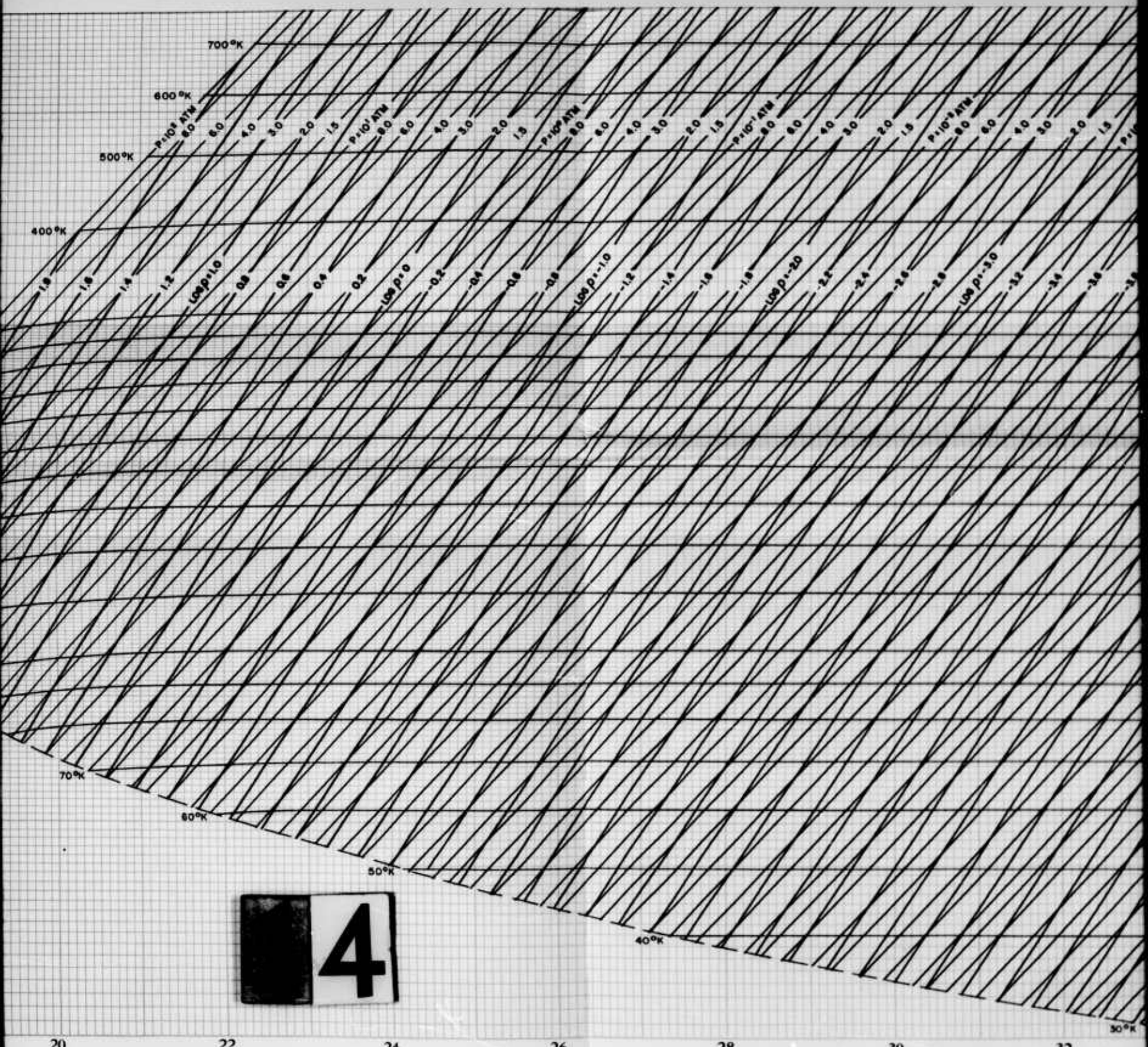

S/R

# DIAGRAM FOR EQUILIBRIUM AIR

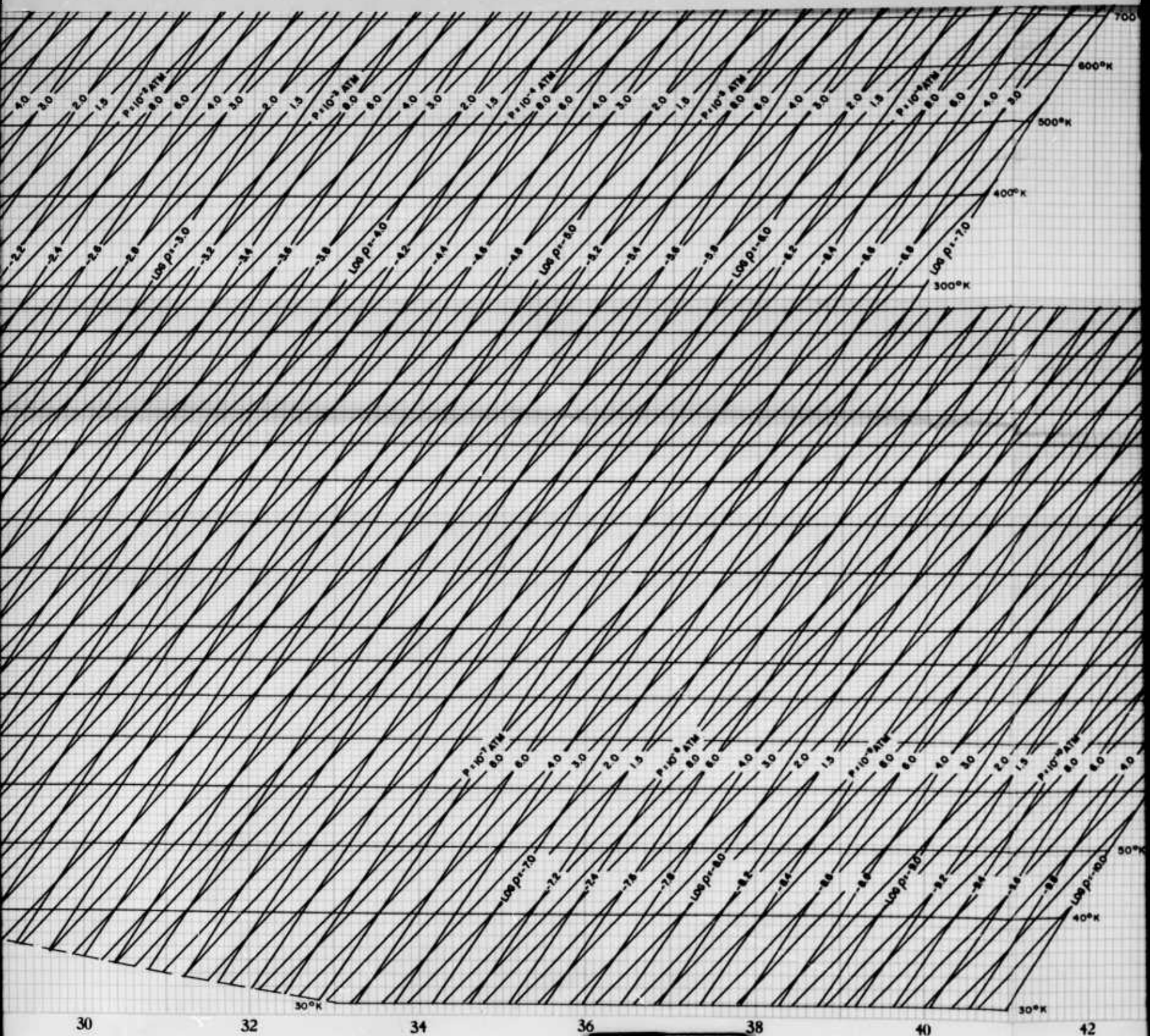
D BY THE STAFF OF VON KARMAN GAS DYNAMICS
, ARO, INC., CONTRACT OPERATORS OF ARNOLD EN-
NG DEVELOPMENT CENTER, UNITED STATES AIR
RNOLD AIR FORCE STATION, TENNESSEE. PRINTED BY
THENON PRESS, NASHVILLE, TENNESSEE, MARCH 1964.

e of sectional parts given by Wanda J. Little, "Mollier Diagram for
September 1963. The data for it are derived from J. Hilsenrath


H/R [°K]
$10^3$
8
6
4
2
$10^2$
14
16
18
20
22
800°K
700°K
600°K
500°K
400°K
300°K
280°K
260°K
240°K
220°K
200°K
180°K
160°K
140°K
120°K
100°K
90°K
80°K
70°K
60°K
P=10³ ATM
LOG p=1.0
LOG p=1.6


700°K
600°K
500°K
400°K
70°K
60°K
50°K
40°K
30°K
P=10⁵ ATM
P=10⁴ ATM
P=10³ ATM
P=10² ATM
P=10¹ ATM
Log p=1.0
Log p=0
Log p=-1.0
Log p=-2.0
Log p=-3.0
20
22
24
26
28
30
32
S/R

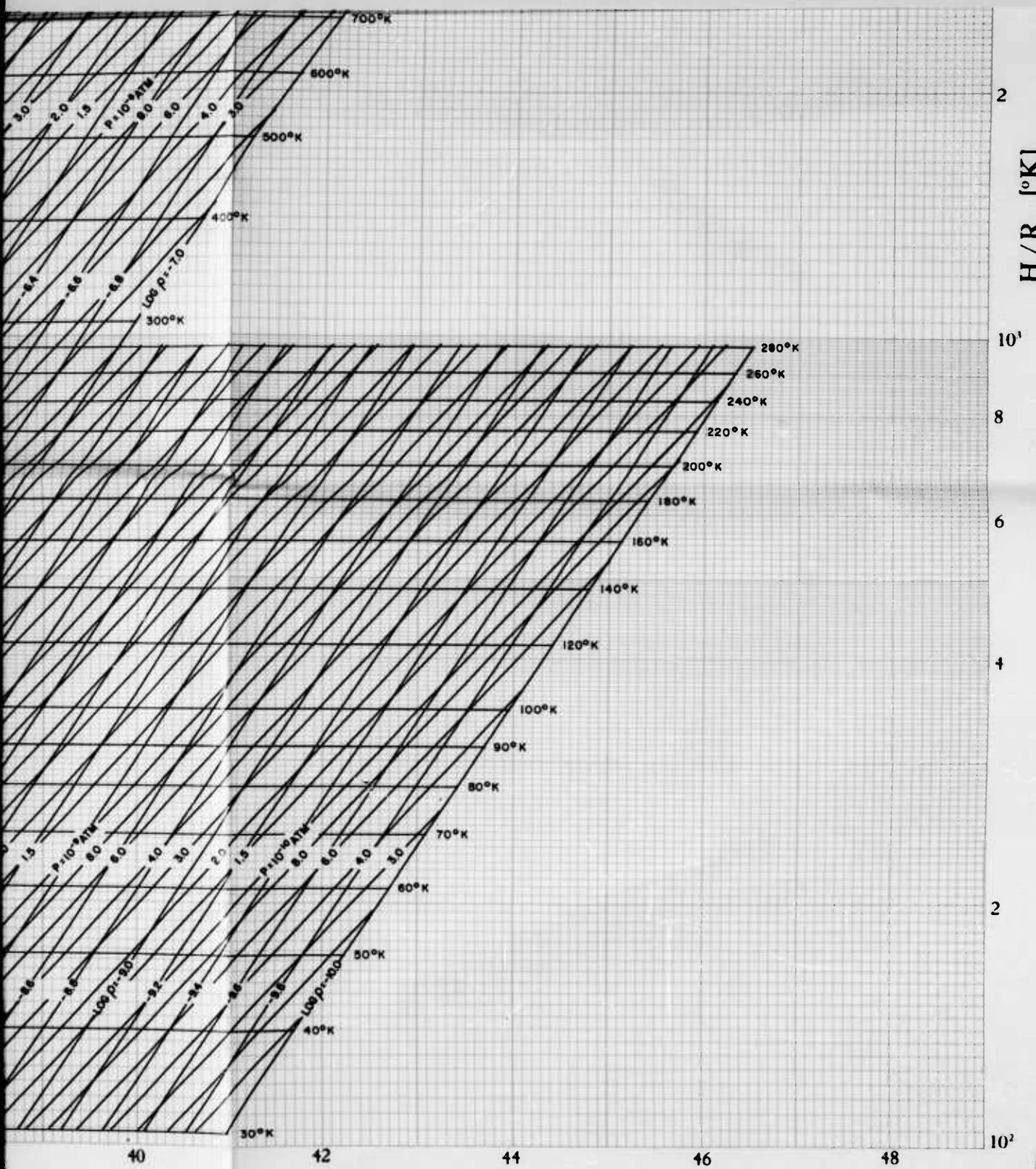
4




30 32 34 36 38 40 42

S/R

[redacted] 5


700°K
600°K
500°K
400°K
300°K
280°K
260°K
240°K
220°K
200°K
180°K
160°K
140°K
120°K
100°K
90°K
80°K
70°K
60°K
50°K
40°K
30°K
P=10⁻⁶ ATM
P=10⁻⁷ ATM
LOG p=-7.0
LOG p=-8.0
LOG p=-9.0
40
42
44
46
48
H/R [°K]
2
10¹
8
6
4
2
10²

GINEERING DEVELOPMENT CENTER, UNITED STATES AIR FORCE, ARNOLD AIR FORCE STATION, TENNESSEE. PRINTED BY THE PARTHENON PRESS, NASHVILLE, TENNESSEE, MARCH 1964.


This chart is a composite of sectional parts given by Wanda J. Little, "Mollier Air," AEDC-TDR-63-190, September 1963. The data for it are derived from and M. Klein, "Tables of Thermodynamic Properties of Air in Chemical Equ cluding Second Virial Corrections from 1500 to 15,000°K," AEDC-TDR-63 1963, and from R. L. Humphrey and C. A. Neel, "Tables of Thermodynamic Air from 90 to 1500°K," AEDC-TR-61-103, August 1961. The latter tables are on J. Hilsenrath, C. W. Beckett, et al., *Tables of Thermal Properties of Gases,* N 564, November 1955, and on F. Din, *Thermodynamic Functions of Gases,* V worths, London, 1956. The tables of Din also provide data for the saturation sures above one atmosphere. At pressures below one atmosphere, the approx tion line is based on G. T. Furukawa and R. E. McCoskey, "The Condensation and the Heats of Vaporization of Oxygen and Nitrogen," NBS Technical Rep gust 1952, and on W. D. Erickson and H. E. Creekmore, "Study of Equilibri Effects in Hypersonic Air Nozzles, Including Charts of Thermodynamic Prope librium Air," NASA-TN-D-231, April 1960.

The vertical coordinate is the enthalpy function H/R expressed in unit Kelvin. Its values are obtained by multiplying the dimensionless function H temperature. The horizontal coordinate is the dimensionless entropy functi temperature T is measured in degrees Kelvin. The pressure p is given in atm the density ρ in amagat units based on the density of air at 0° C and a pressure phere. The logarithms are common logarithms to base ten.

For air, one amagat is the equivalent of 0.00129 grams per cubic centimet pounds per cubic foot. Enthalpy in calories per gram is equal to H/R(°K) 0.0686 and in British thermal units per pound it is equal to H/R(°K) multipli The specific enthalpy in feet-squared per second-squared is equal to H/R(°K by 3092.0 and in meters-squared per second-squared to H/R(°K) multiplied

GINEERING DEVELOPMENT CENTER, UNITED STATES AIR FORCE, ARNOLD AIR FORCE STATION, TENNESSEE. PRINTED BY THE PARTHENON PRESS, NASHVILLE, TENNESSEE, MARCH 1964.

This chart is a composite of sectional parts given by Wanda J. Little, "Mollier Diagram for Air," AEDC-TDR-63-190, September 1963. The data for it are derived from J. Hilsenrath and M. Klein, "Tables of Thermodynamic Properties of Air in Chemical Equilibrium Including Second Virial Corrections from 1500 to 15,000°K," AEDC-TDR-63-161, August 1963, and from R. L. Humphrey and C. A. Neel, "Tables of Thermodynamic Properties of Air from 90 to 1500°K," AEDC-TR-61-103, August 1961. The latter tables are based mainly on J. Hilsenrath, C. W. Beckett, et al., *Tables of Thermal Properties of Gases,* NBS Circular 564, November 1955, and on F. Din, *Thermodynamic Functions of Gases,* Vol. 2, Butterworths, London, 1956. The tables of Din also provide data for the saturation line at pressures above one atmosphere. At pressures below one atmosphere, the approximate saturation line is based on G. T. Furukawa and R. E. McCoskey, "The Condensation Line of Air and the Heats of Vaporization of Oxygen and Nitrogen," NBS Technical Report 1775, August 1952, and on W. D. Erickson and H. E. Creekmore, "Study of Equilibrium Real-Gas Effects in Hypersonic Air Nozzles, Including Charts of Thermodynamic Properties of Equilibrium Air," NASA-TN-D-231, April 1960.

The vertical coordinate is the enthalpy function H/R expressed in units of degrees Kelvin. Its values are obtained by multiplying the dimensionless function H/RT by the temperature. The horizontal coordinate is the dimensionless entropy function S/R. The temperature T is measured in degrees Kelvin. The pressure p is given in atmospheres, and the density $\rho$ in amagat units based on the density of air at 0° C and a pressure of one atmosphere. The logarithms are common logarithms to base ten.

For air, one amagat is the equivalent of 0.00129 grams per cubic centimeter or 0.0807 pounds per cubic foot. Enthalpy in calories per gram is equal to H/R(°K) multiplied by 0.0686 and in British thermal units per pound it is equal to H/R(°K) multiplied by 0.1234. The specific enthalpy in feet-squared per second-squared is equal to H/R(°K) multiplied by 3092.0 and in meters-squared per second-squared to H/R(°K) multiplied by 287.2.

AEDC-TDR-63-190




# MOLLIER DIAGRAM FOR AIR

By

Wanda J. Little
von Kármán Gas Dynamics Facility
ARO, Inc.

TECHNICAL DOCUMENTARY REPORT NO. AEDC-TDR-63-190

September 1963

Program Element 61405014/8951, Task 89603

(Prepared under Contract No. AF 40(600)-1000 by ARO, Inc., contract operator of AEDC, Arnold Air Force Station, Tenn.)

ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE



## ABSTRACT

A Mollier diagram for air, including the effects of dissociation and ionization, as well as of intermolecular potentials to the second virial correction, is presented. The range of temperatures extends from the saturation line to 15, 000°K and the range of densities, from $10^{-7}$ to approximately 200 amagats.


## PUBLICATION REVIEW

**This report has been reviewed and publication is approved.**


Larry D. Fitzgerald
Capt, USAF
Aerospace Sciences Division
DCS/Research

Donald R. Eastman, Jr.
DCS/Research

## CONTENTS



## ILLUSTRATIONS

## NOMENCLATURE

| | |
|---|---|
| H/R | Enthalpy in °K, obtained by multiplying the dimensionless function H/RT by the temperature in °K |
| log | Common logarithm to base 10 |
| p | Pressure, atm |
| R | Gas constant |
| S/R | Entropy, dimensionless |
| T | Temperature, °K |
| $\rho/\rho_o$ | Density in amagats, based on $\rho_o$ at 0°C and one atm of pressure |

## 1.0 INTRODUCTION

This air Mollier diagram was prepared for the purposes of data reduction in the operation of wind tunnels at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), USAF. This diagram represents the most recently available information on the thermodynamic properties of air, including the effects of dissociation, ionization, and of intermolecular potentials to the second virial correction. The diagram covers the range of temperatures from the saturation line to 15,000°K and the range of densities from $10^{-7}$ to from 200 to 250 amagats. Above 1500°K, the plotted data are taken from the tables of Hilsenrath and Klein (Ref. 1), whereas the data below 1500°K are derived from the tables of Humphrey and Neel (Ref. 2) which combine information from various sources, notably the tables of Din (Ref. 3). Data below 90°K, as well as all data at densities below $10^{-7}$ amagat, were generated mainly by extrapolation, using the method described in Ref. 4. The tables of Din (Ref. 3) provide explicit data for the saturation line at pressures from one atmosphere upwards. At pressures below one atmosphere, the saturation line is based on the work of Furukawa and McCoskey (Ref. 5) and of Erickson and Creekmore (Ref. 6), the latter being based on vapor-pressure data for pure nitrogen and oxygen.

Enthalpy, expressed as H/R having dimensions of degrees Kelvin, is plotted vertically on a logarithmic scale through four decimal orders of magnitude. The dimensionless entropy, S/R, is the other basic variable. Lines at constant density are identified by their values of $\log \rho/\rho_o$, in which the ratio $\rho/\rho_o$ is the density in amagats. The constant pressure lines are marked in atmospheres and the constant temperature in degrees Kelvin.

The appendix contains a short list of useful conversion factors.

## REFERENCES

1. Hilsenrath, J., and Klein, M. "Tables of Equilibrium Properties of Air Including Second Virial Corrections." AEDC-TDR-63-161. September 1963.

2. Humphrey, R. L., and Neel, C. A. "Tables of the Thermodynamic Properties of Air from 90 to 1500°K." AEDC-TN-61-103, August 1961.

---

Manuscript received August 1963.

3. Din, F. Thermodynamic Functions of Gases. Vol. 1, Butterworths Scientific Publications, London, 1961.

4. Humphrey, R. L., Little, W. J., and Seely, L. A. "Mollier Diagram for Nitrogen." AEDC-TN-60-83, May 1960.

5. Furukawa, G. T., and McCoskey, R. E. "The Condensation Line of Air and the Heats of Vaporization of Oxygen and Nitrogen." National Bureau of Standards Technical Report 1775, August 1, 1952.

6. Erickson, W. D., and Creekmore, H. S. "A Study of Equilibrium Real-Gas Effects in Hypersonic Air Nozzles, Including Charts of Thermodynamic Properties of Equilibrium Air." NASA TN D-231, April 1960.

## APPENDIX

| Conversion Factors To Change | To | With Units of | Multiply by |
|---|---|---|---|
| $\frac{H}{R}$ | $\frac{H}{RT}$ | None | $\frac{1}{T\,(°K)}$ |
| | $\frac{H}{R}$ | °R | 1.8 |
| | H | $\frac{ft^2}{sec^2}$ | $3.09235(10)^3$ |
| | | $\frac{Btu}{lb}$ | $1.23406(10)^{-1}$ |
| | | $\frac{cal}{gm}$ | $6.86042(10)^{-2}$ |
| $\frac{S}{R}$ | S | $\frac{ft^2}{sec^2\,°K}$ | $3.09235(10)^3$ |
| | | $\frac{ft^2}{sec^2\,°R}$ | $1.71797(10)^3$ |
| | | $\frac{Btu}{lb\,°R}$ | $6.85590(10)^{-2}$ |
| | | $\frac{Btu}{lb\,°K}$ | $1.23406(10)^{-1}$ |
| | | $\frac{cal}{gm\,°K}$ | $6.86402(10)^{-2}$ |
| $\frac{\rho}{\rho_o}$ | $\rho$ | $\frac{gm}{cm^3}$ | $1.29304(10)^{-3}$ |
| | | $\frac{lb}{in.^3}$ | $4.67143(10)^{-5}$ |
| | | $\frac{lb}{ft^3}$ | $8.07223(10)^{-2}$ |

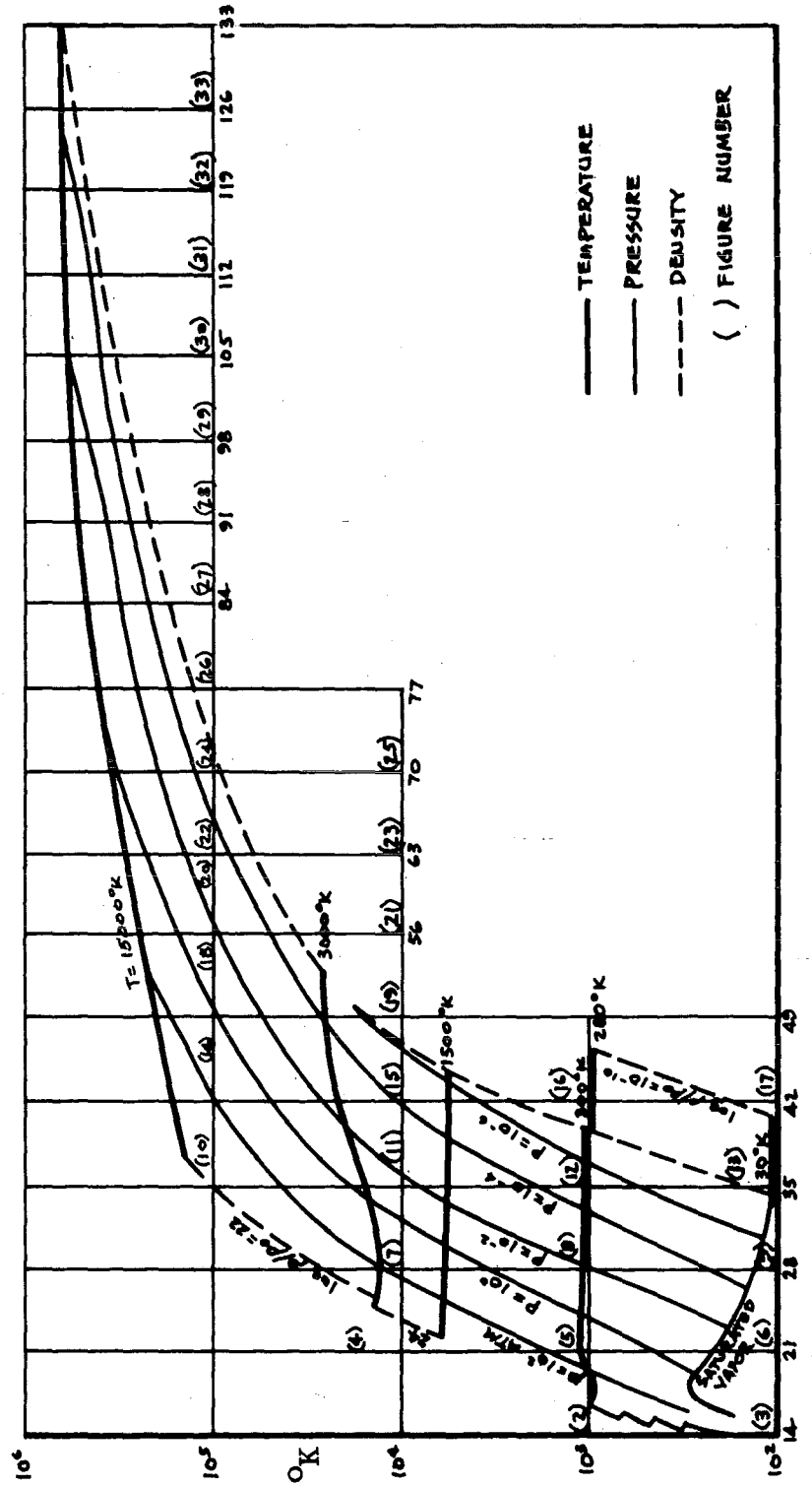



Fig. 1 Index Sheet

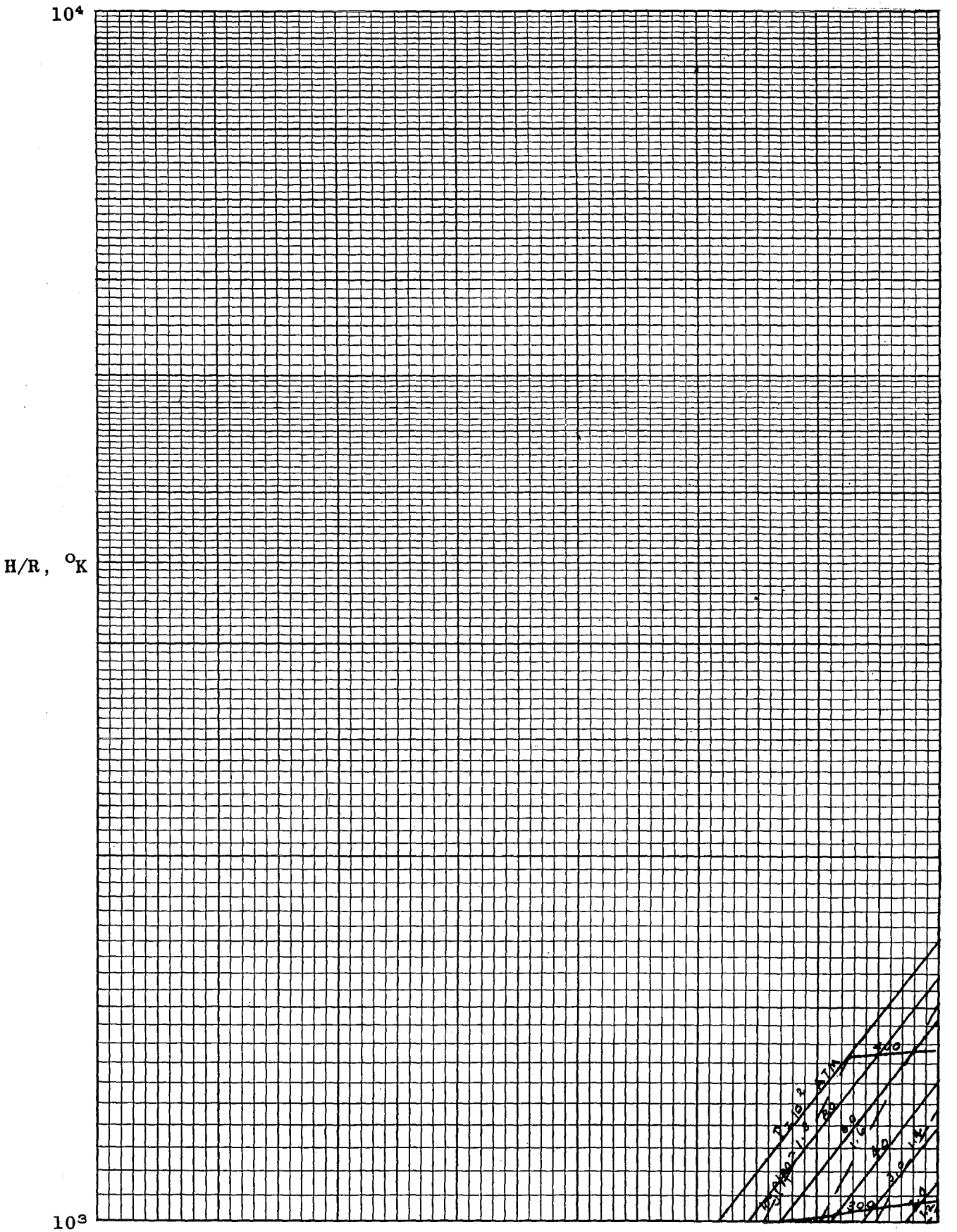



Fig. 2 Air Mollier Diagram

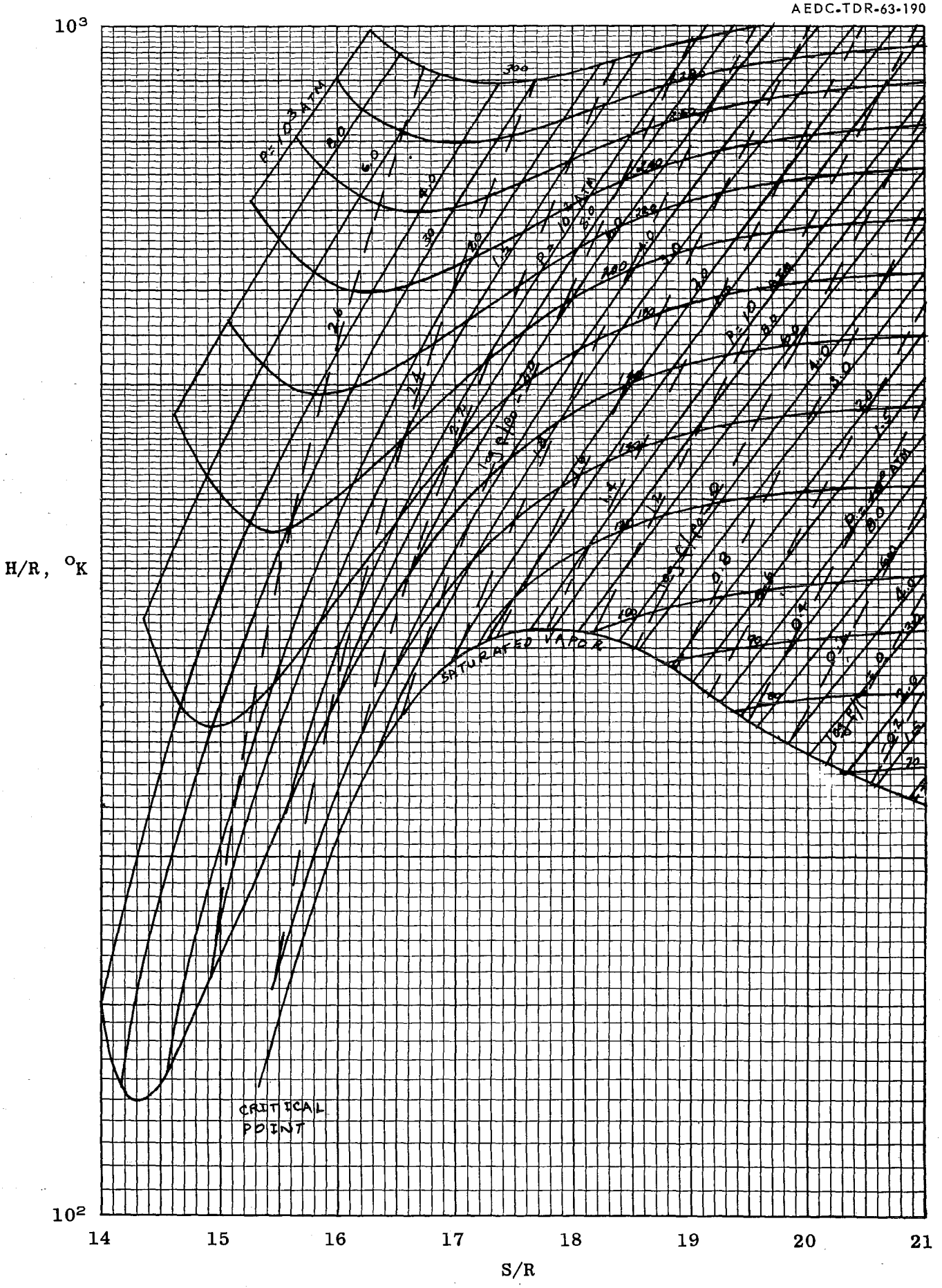



Fig. 3 Air Mollier Diagram

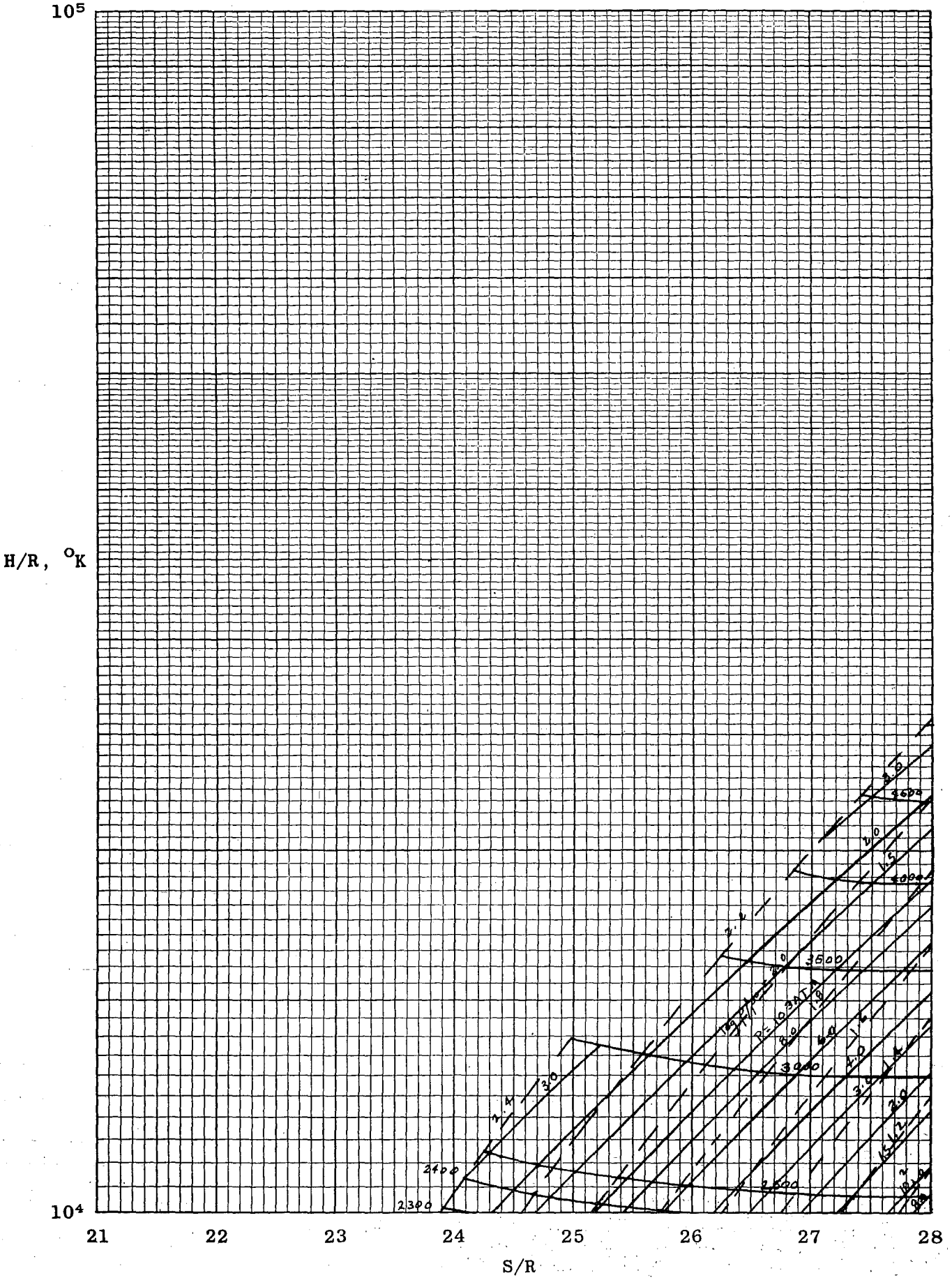



Fig. 4 Air Mollier Diagram

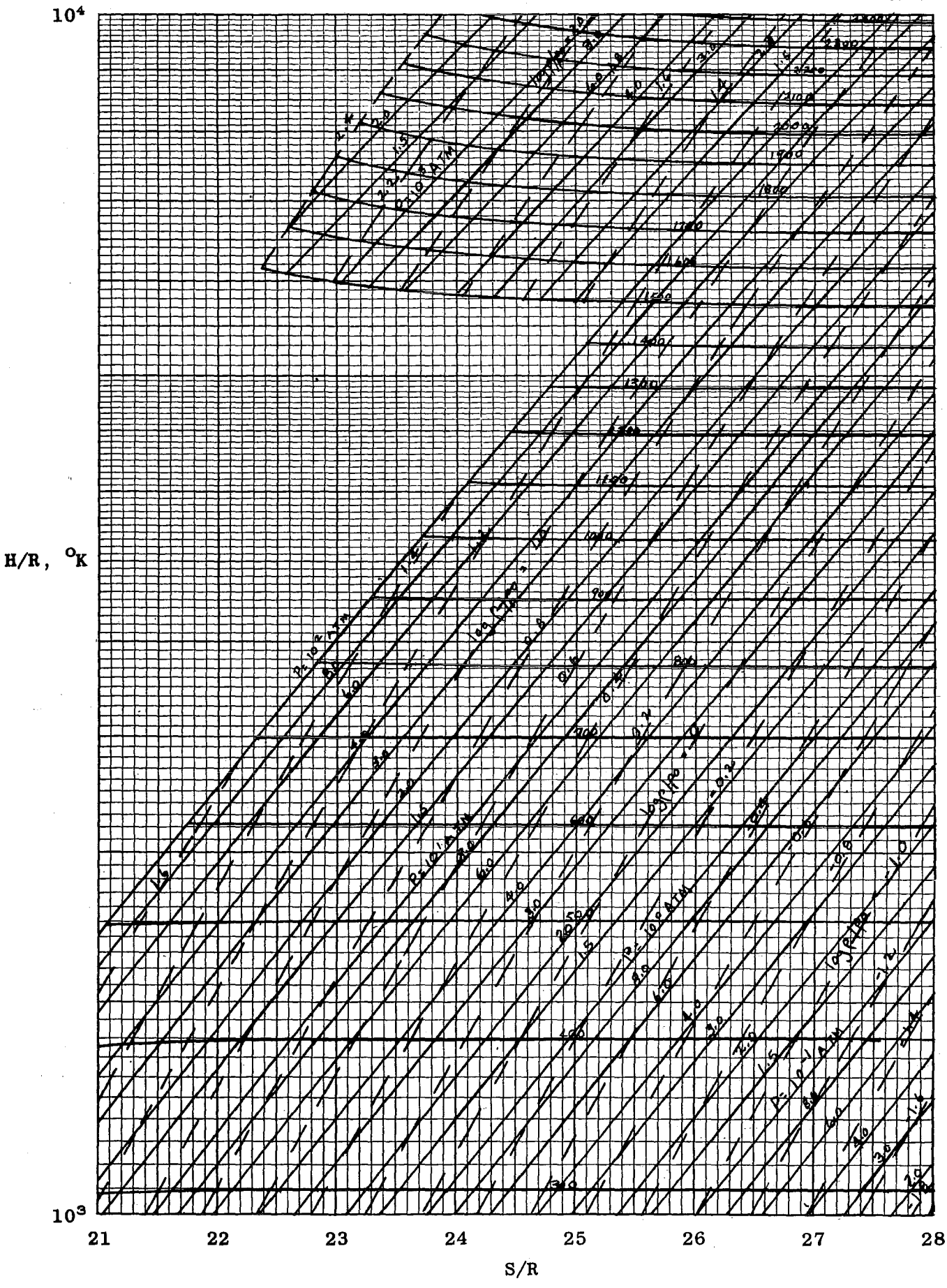



Fig. 5 Air Mollier Diagram

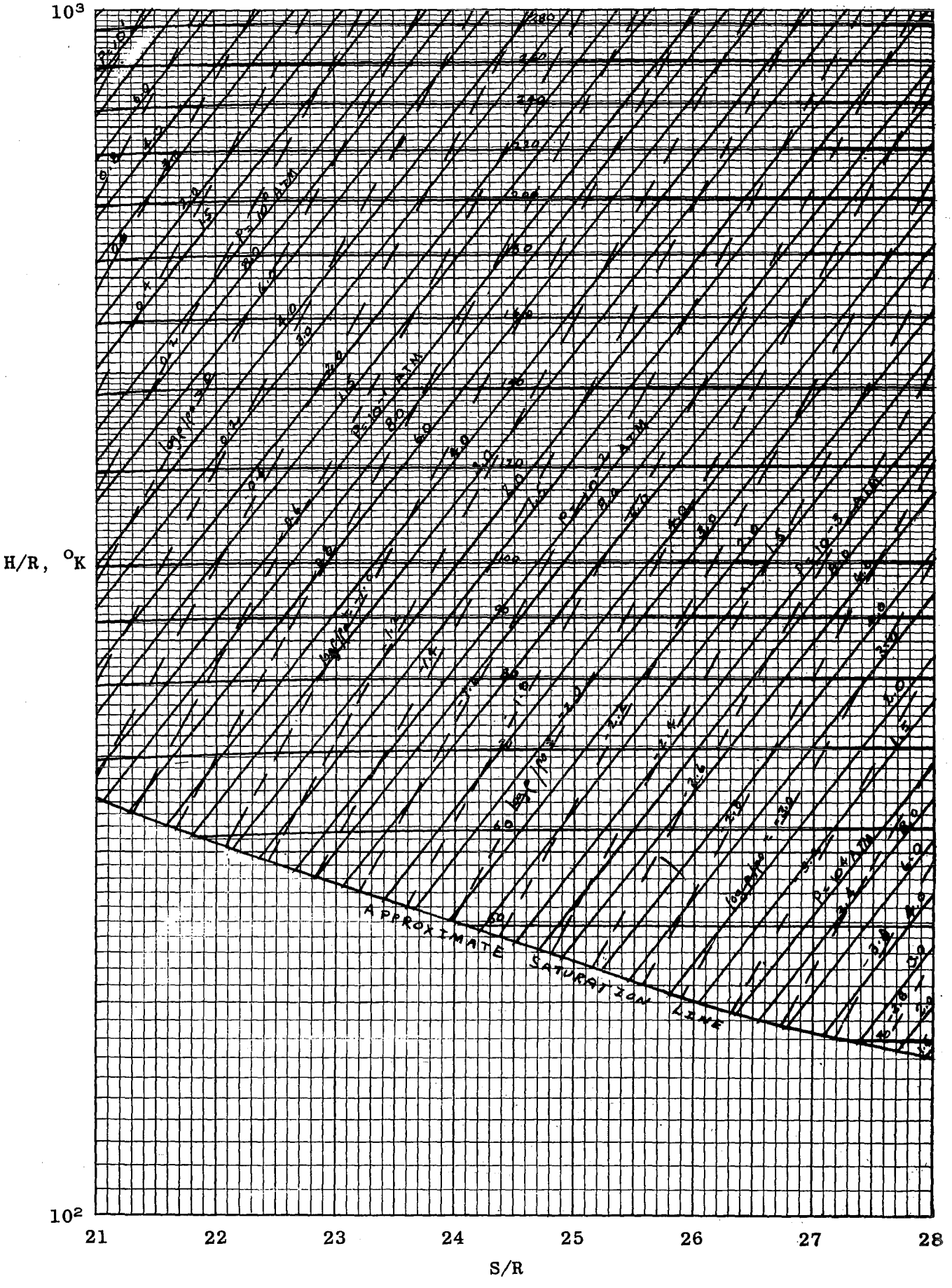



Fig. 6 Air Mollier Diagram

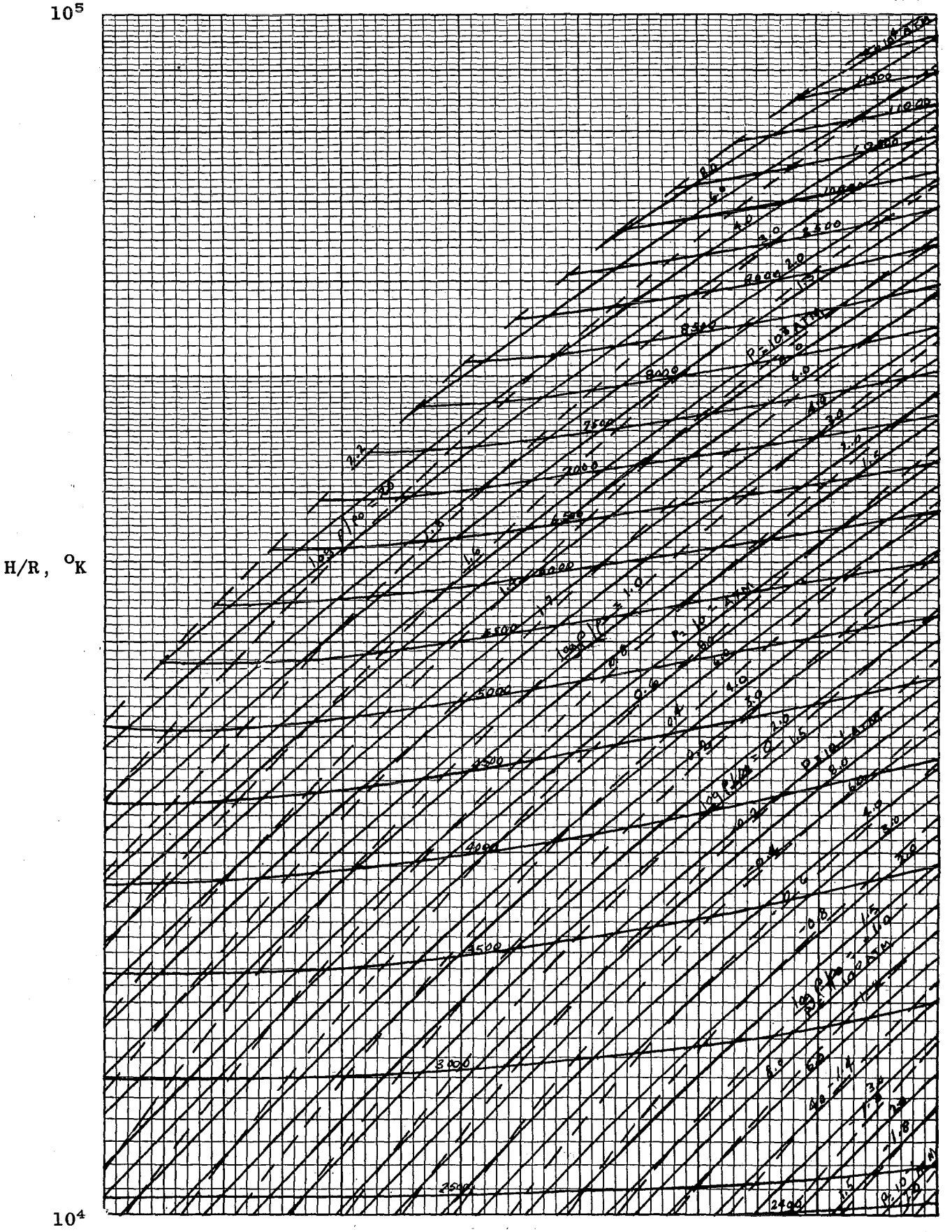



Fig. 7 Air Mollier Diagram

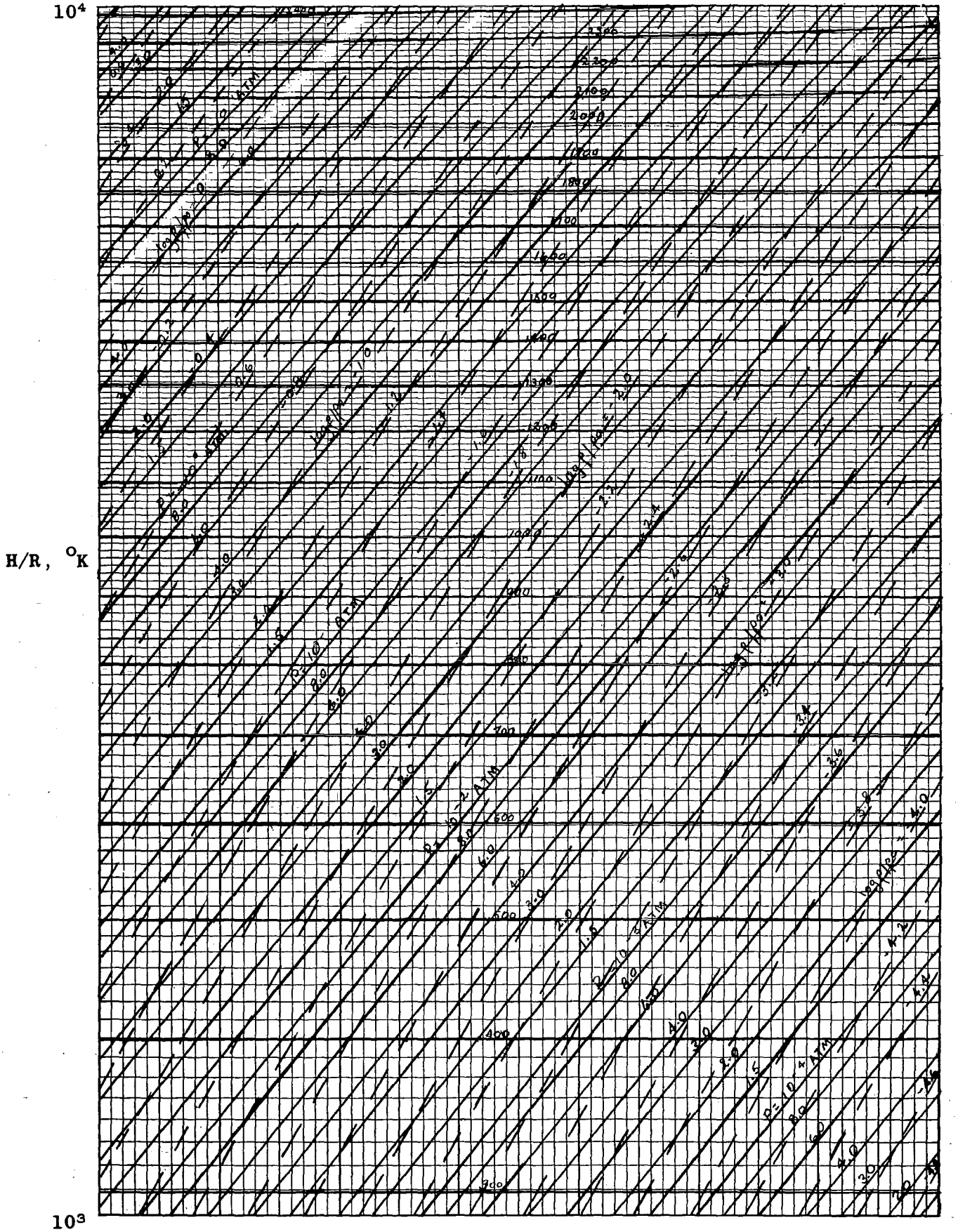



Fig. 8 Air Mollier Diagram

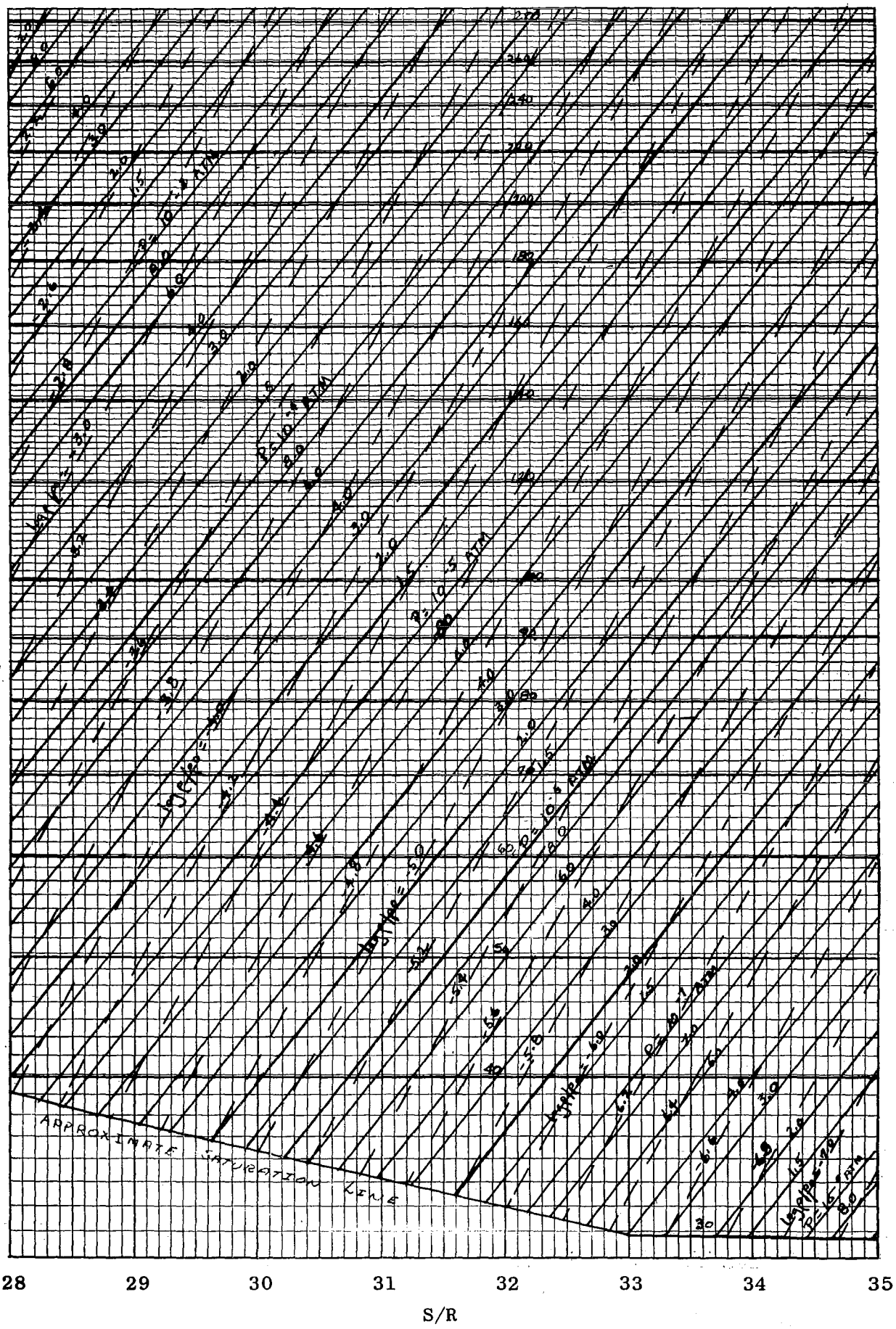



Fig. 9 Air Mollier Diagram

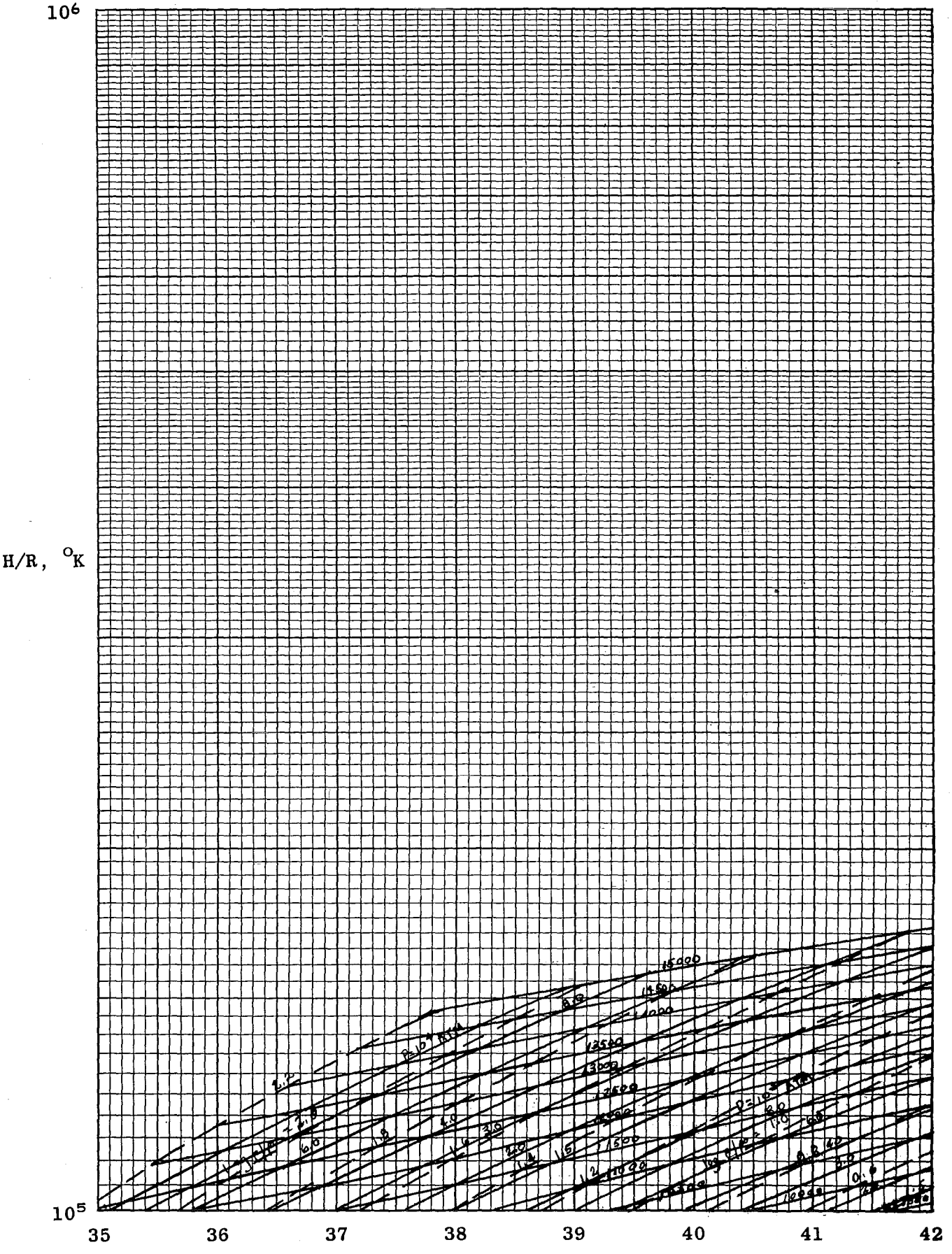



Fig. 10 Air Mollier Diagram

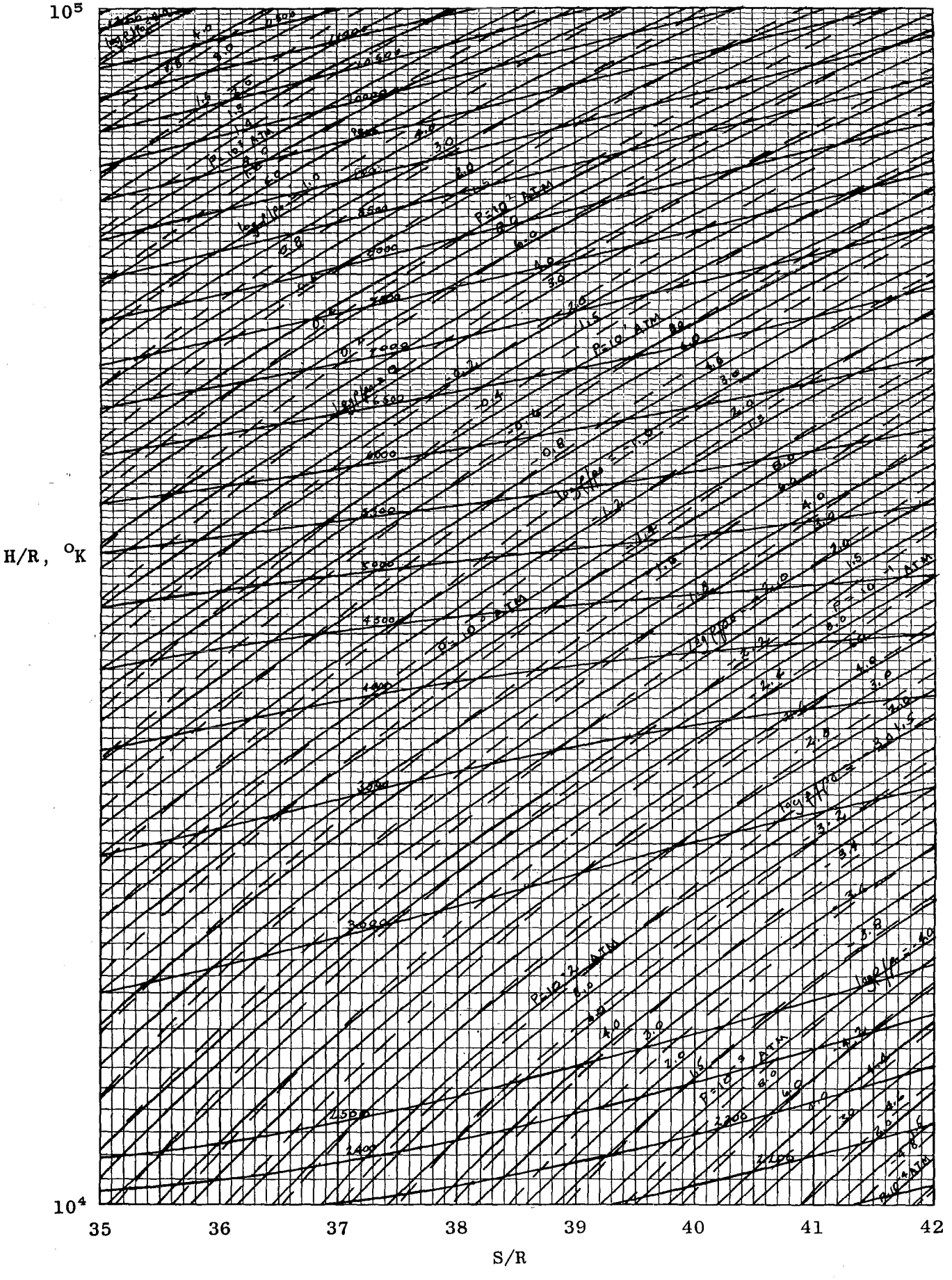



Fig. 11 Air Mollier Diagram

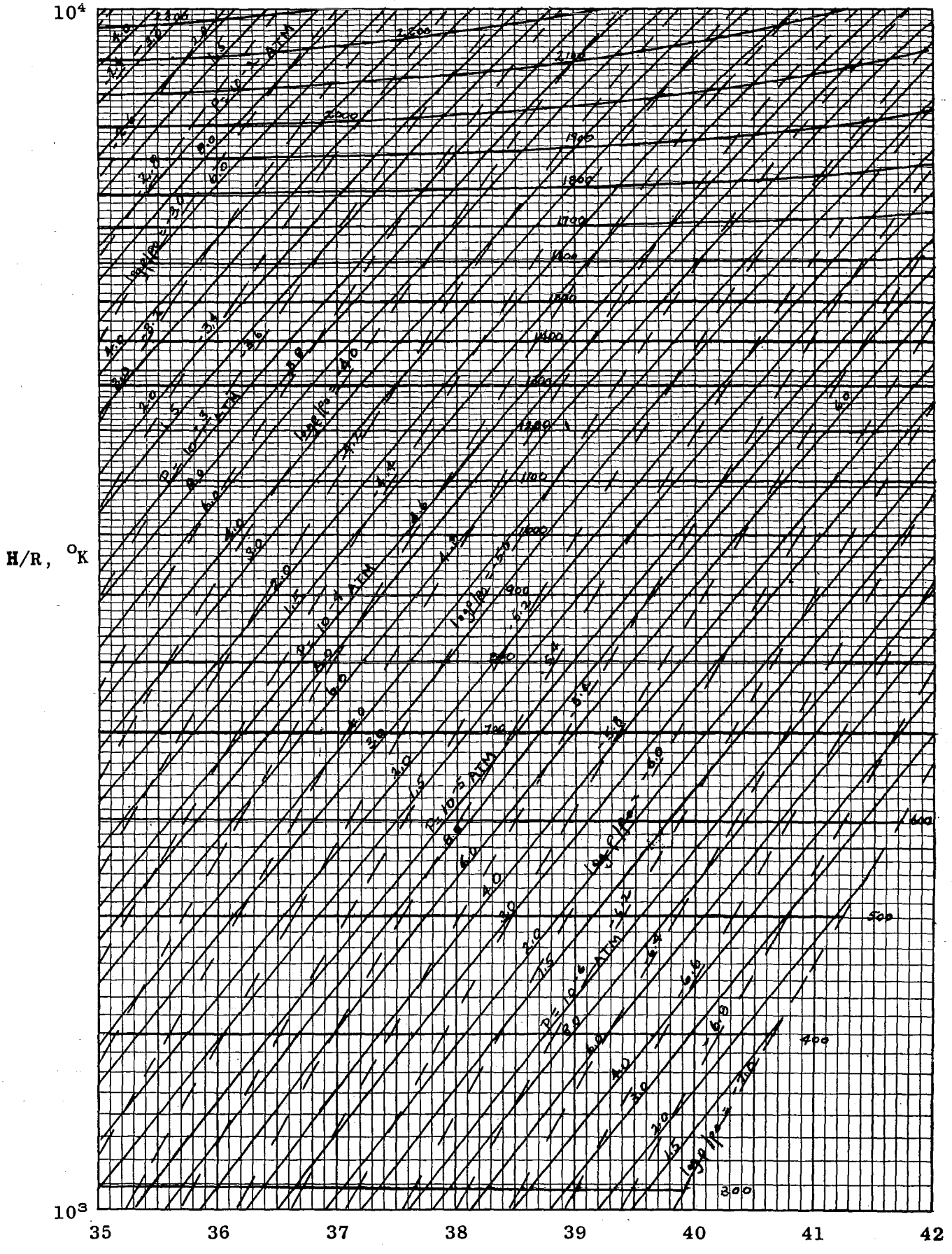



Fig. 12 Air Mollier Diagram

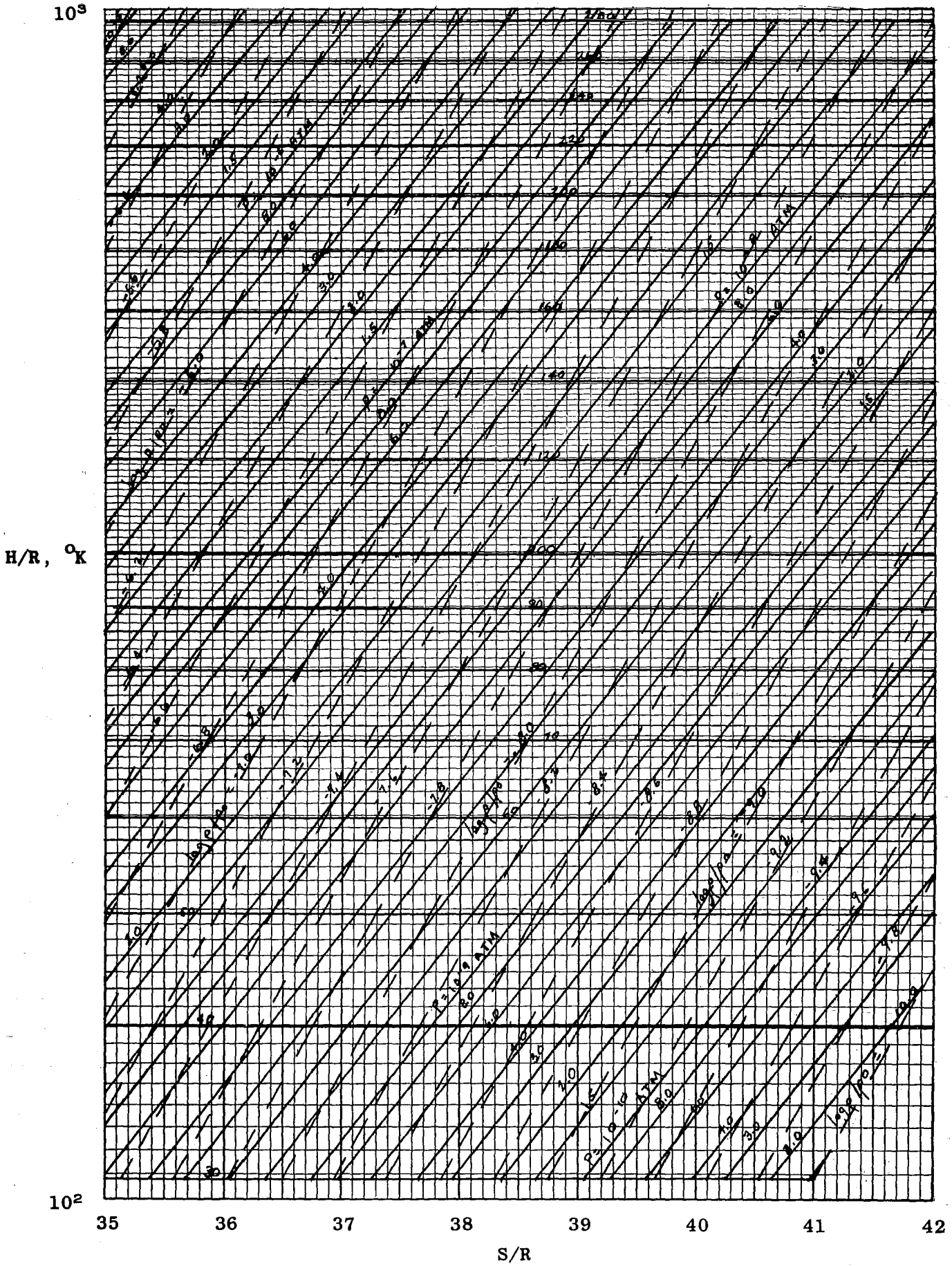



Fig. 13 Air Mollier Diagram

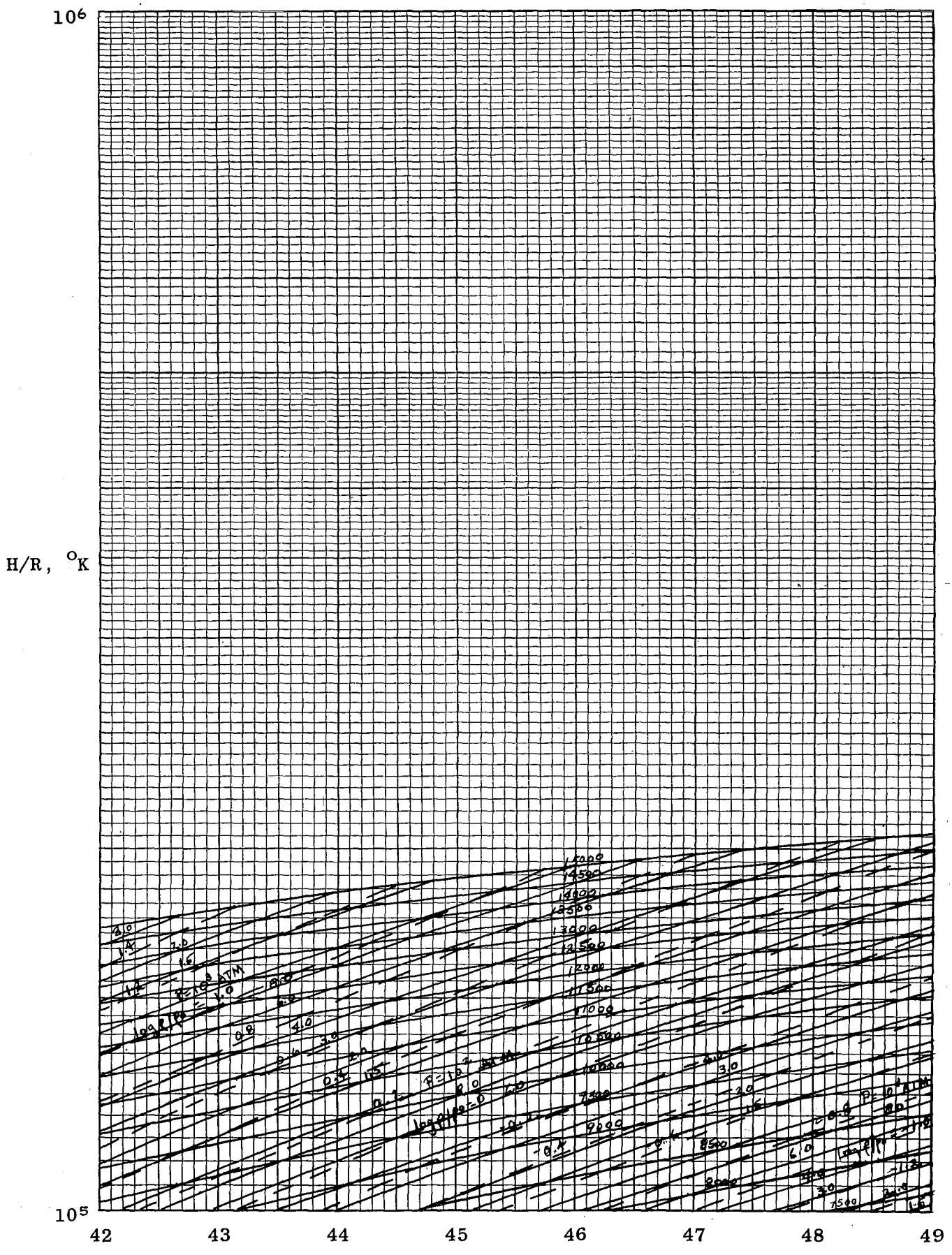



Fig. 14 Air Mollier Diagram

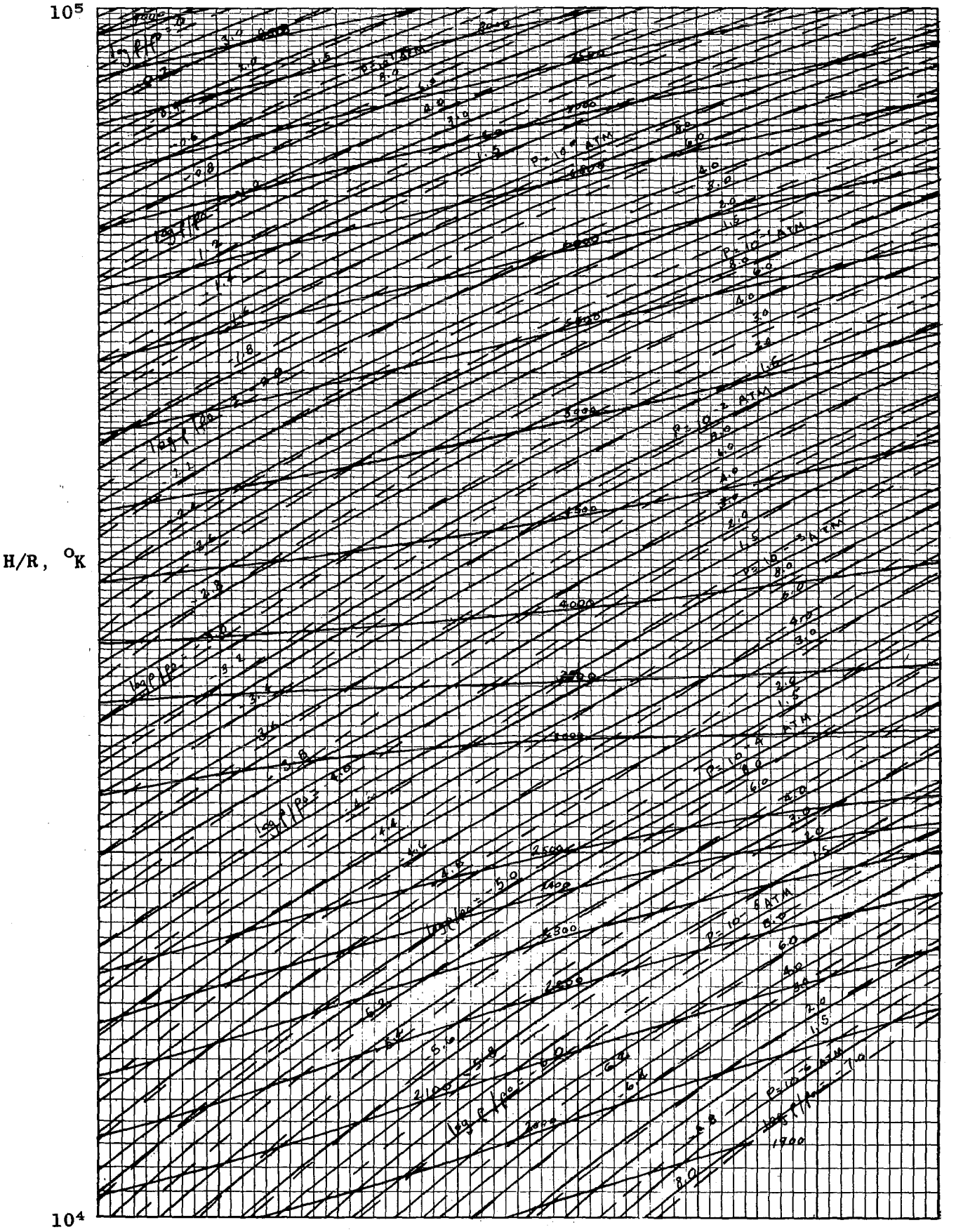



Fig. 15 Air Mollier Diagram

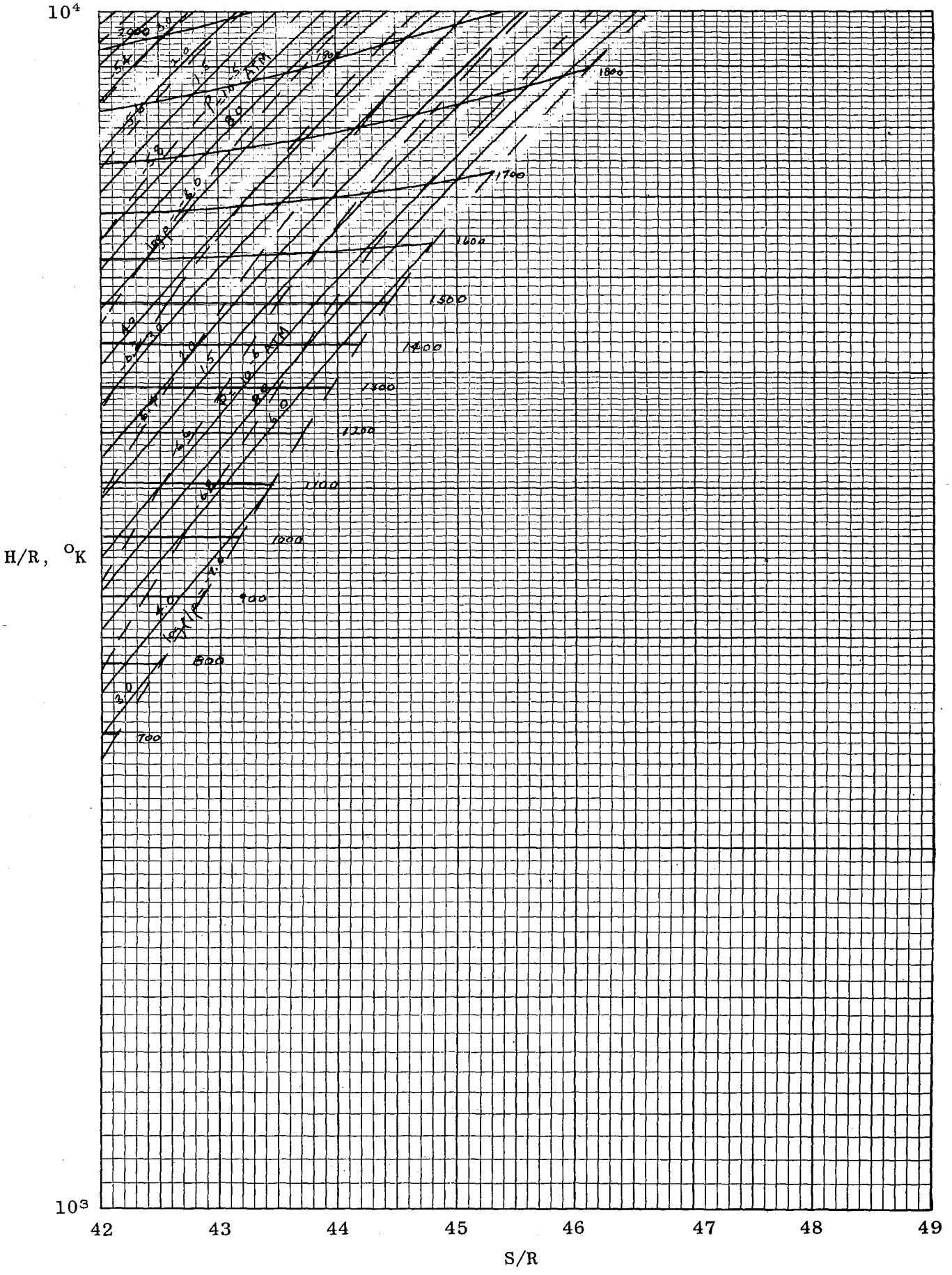



Fig. 16 Air Mollier Diagram

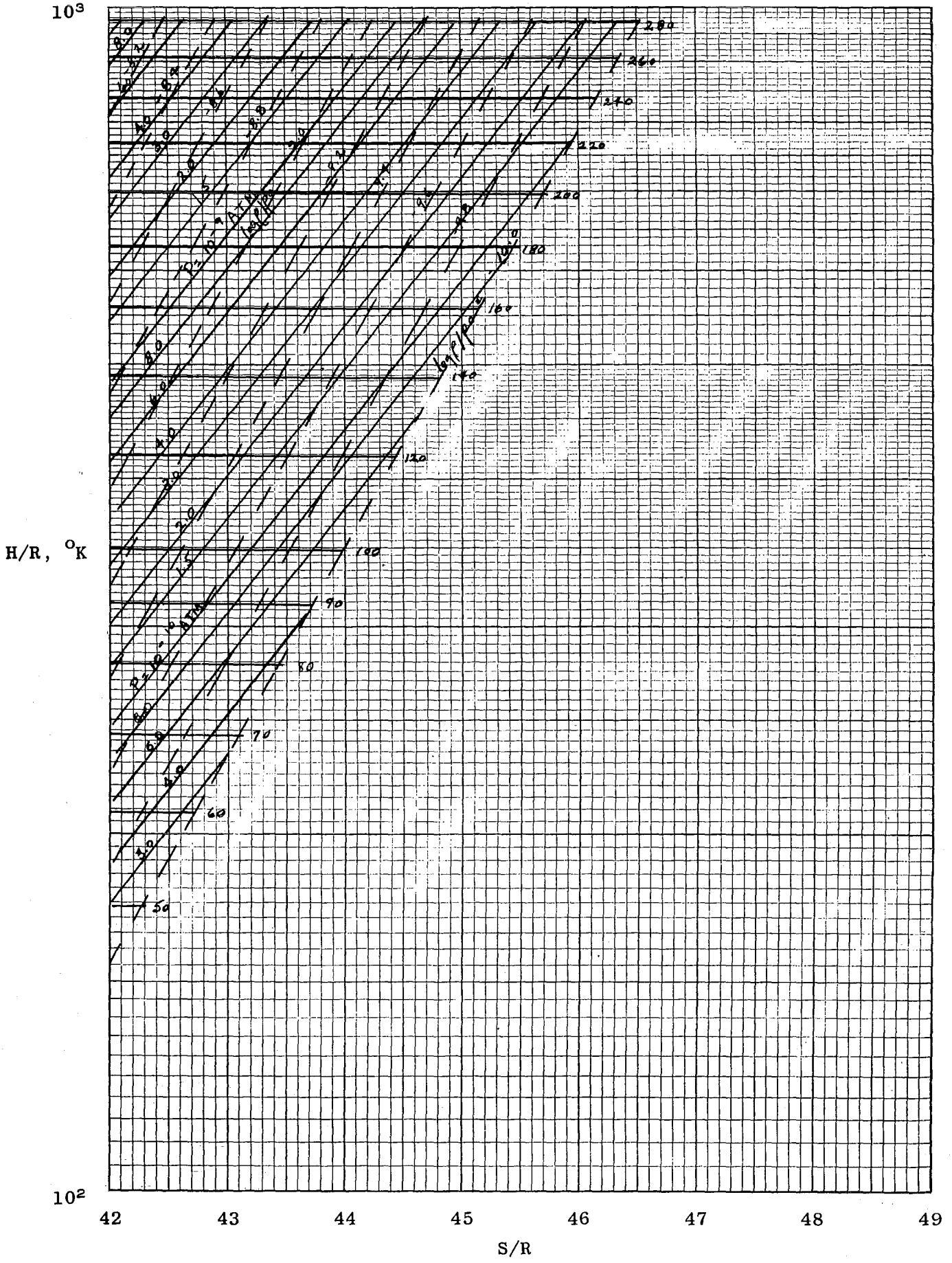



Fig. 17 Air Mollier Diagram

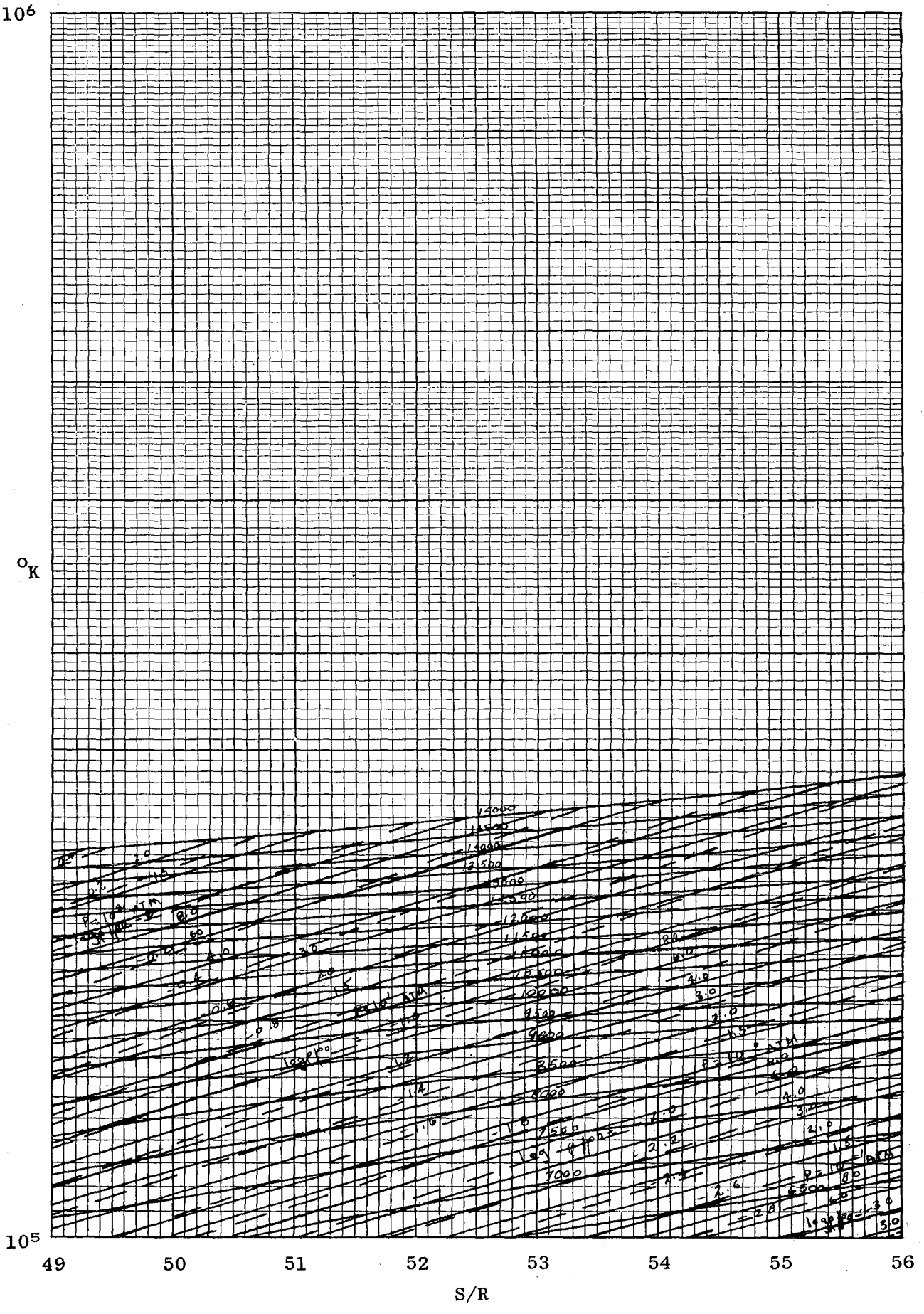



Fig. 18 Air Mollier Diagram

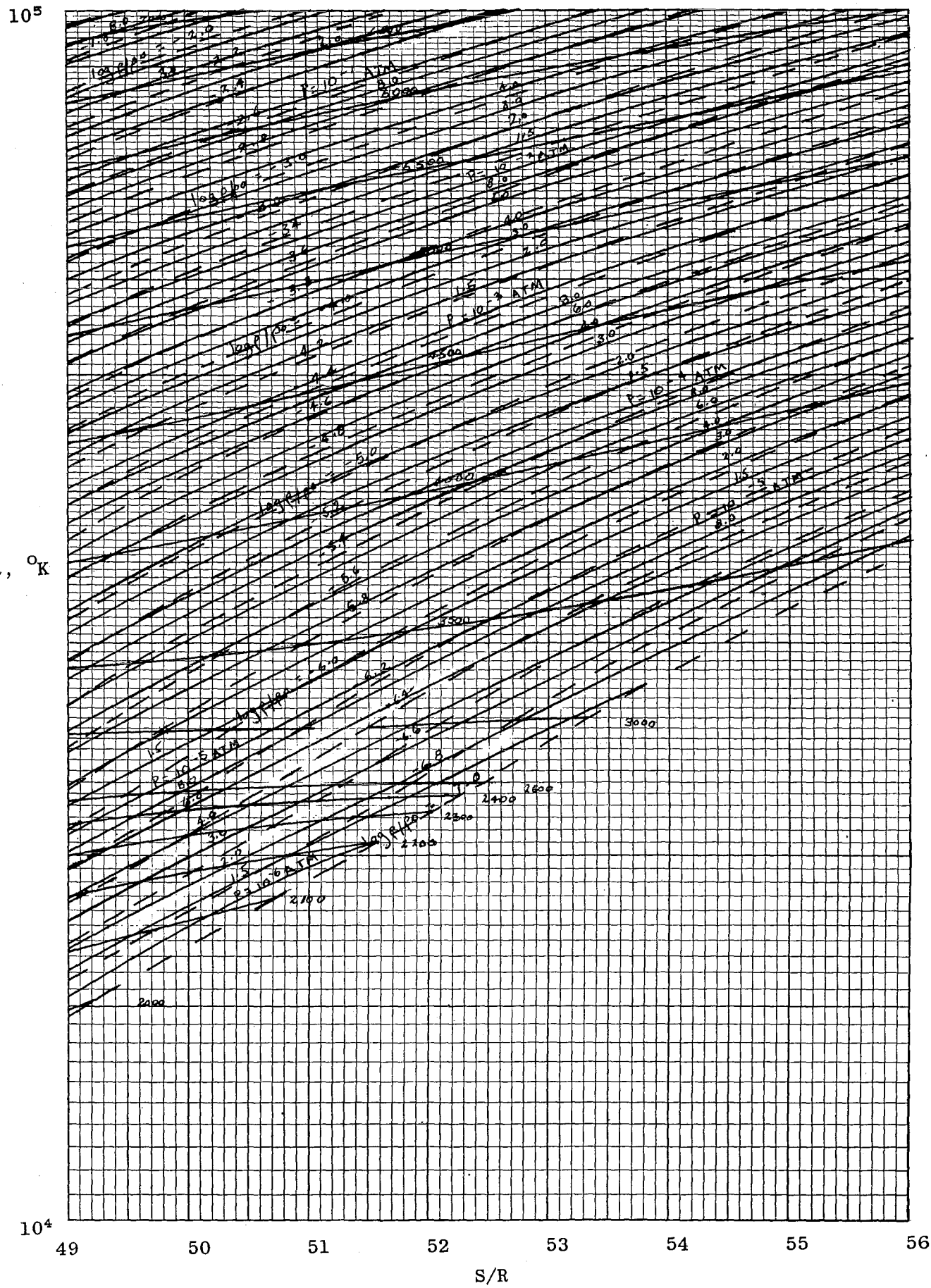



Fig. 19 Air Mollier Diagram

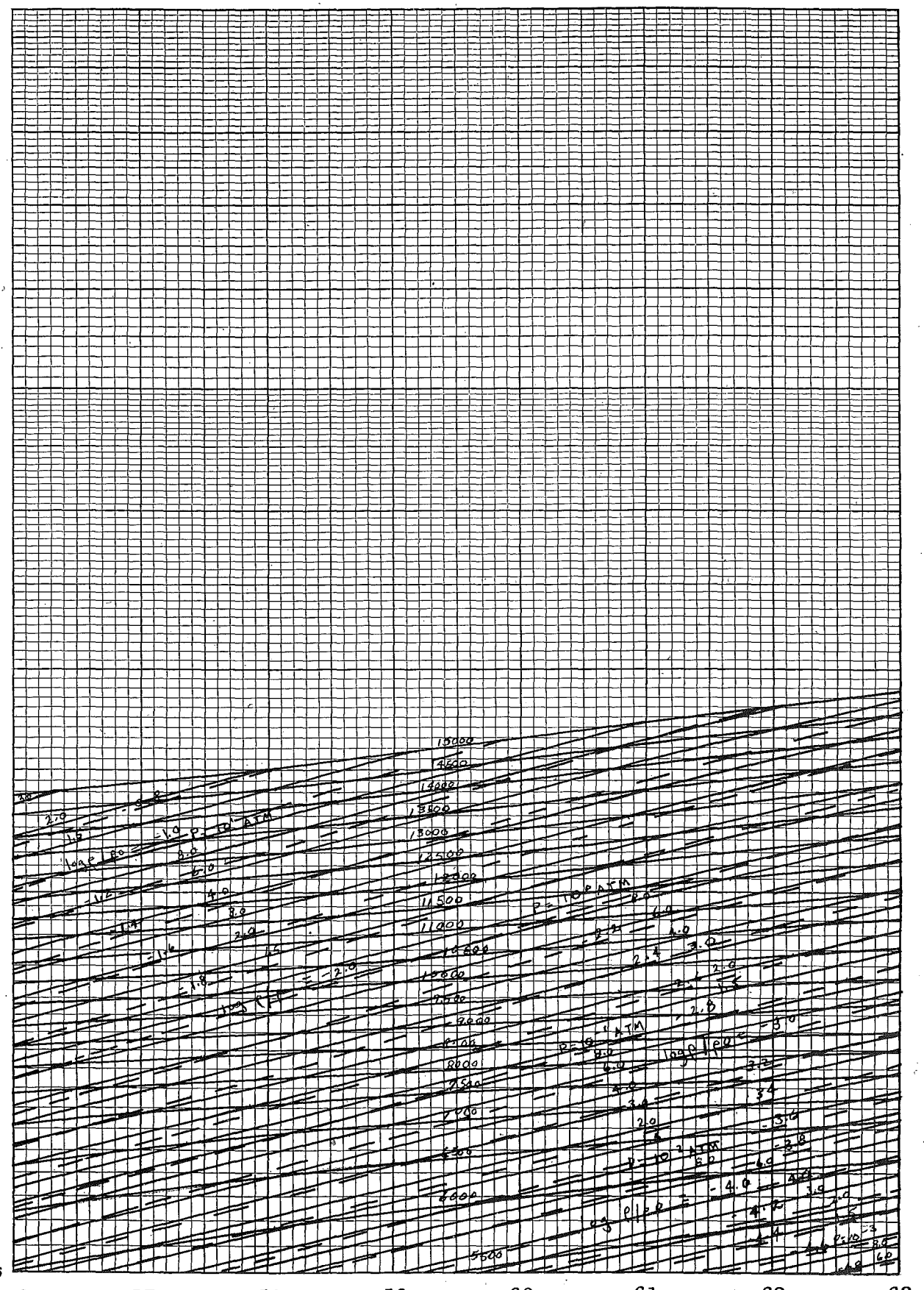



Fig. 20 Air Mollier Diagram

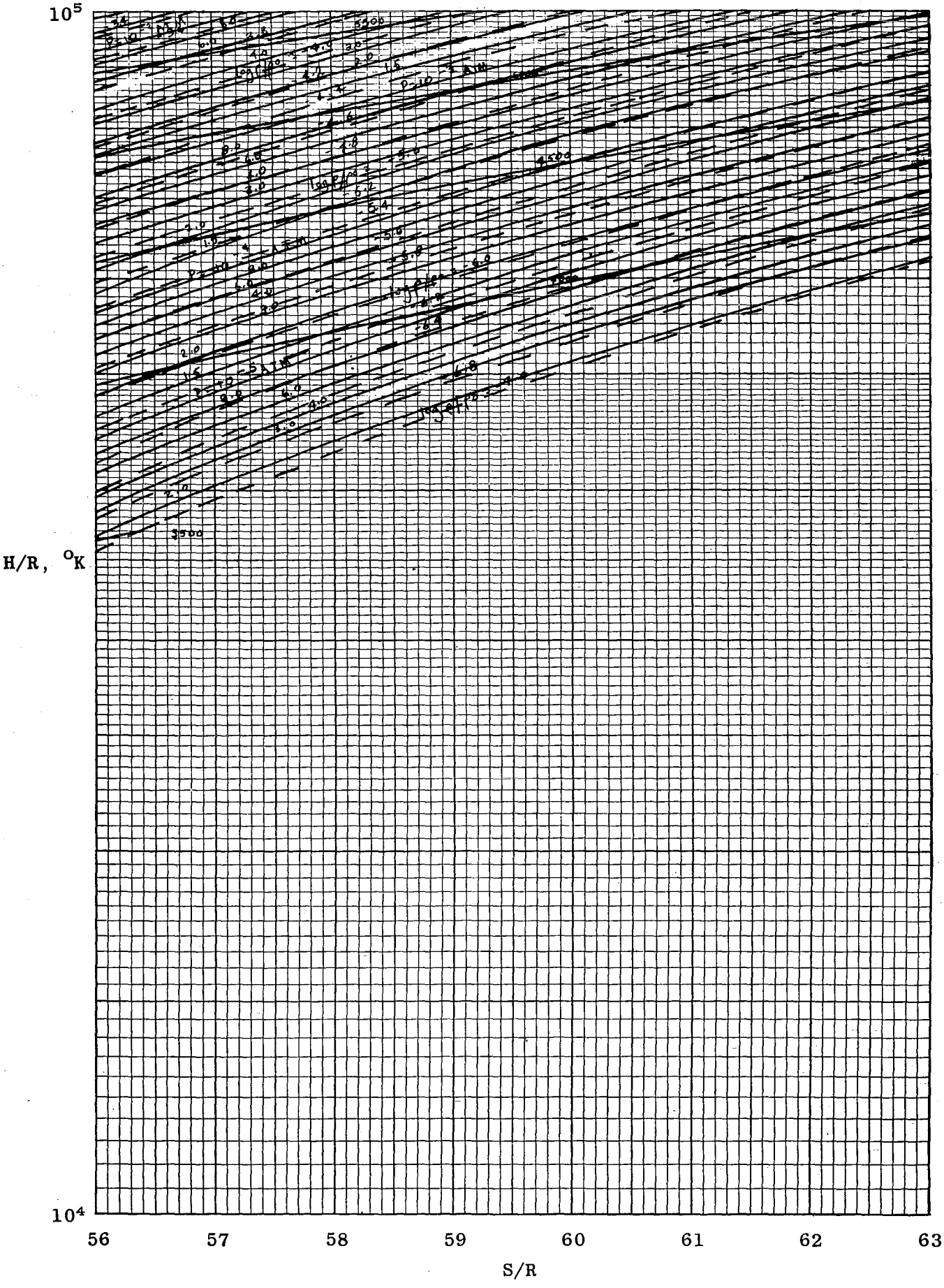



Fig. 21 Air Mollier Diagram

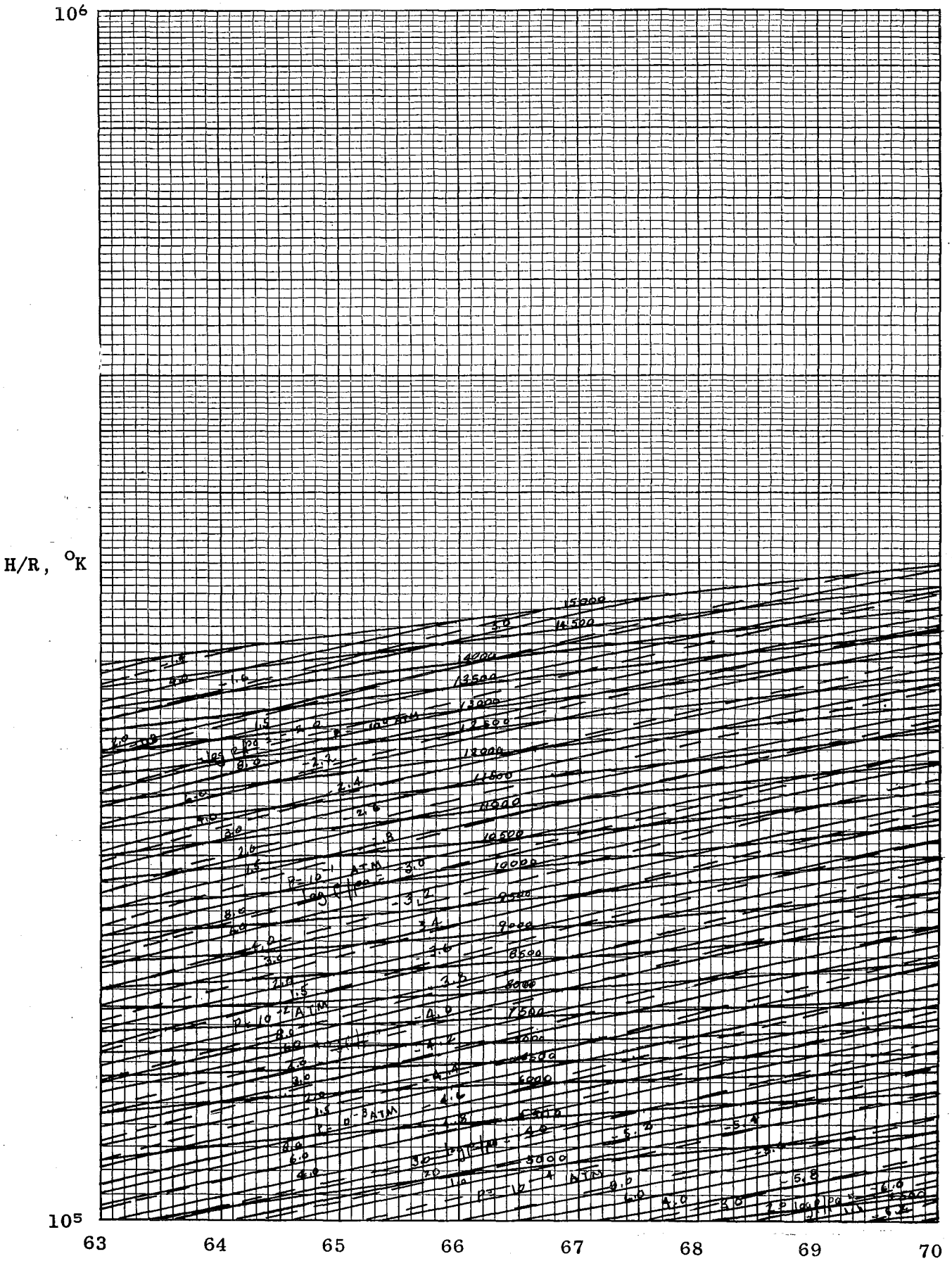



Fig. 22 Air Mollier Diagram

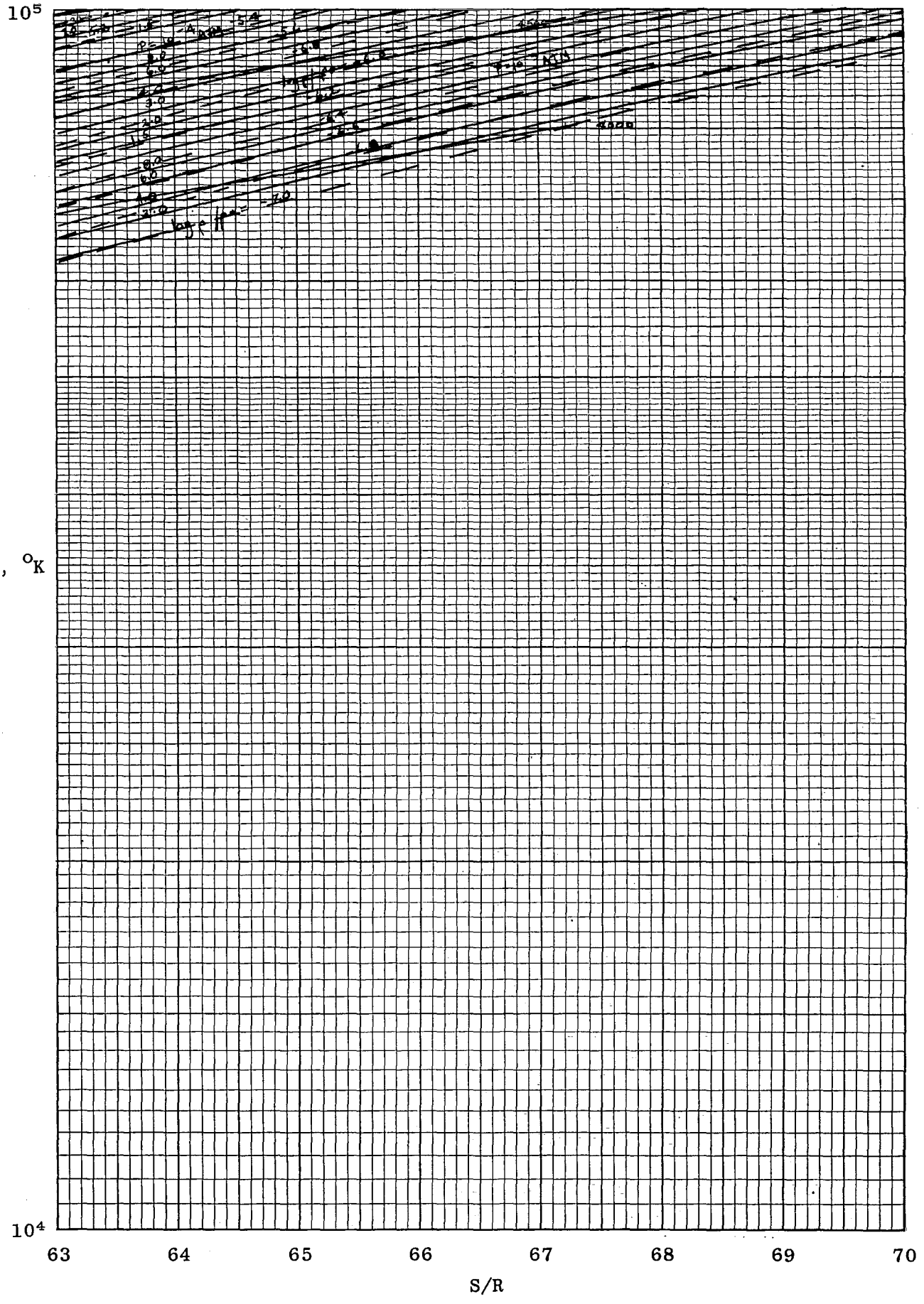



Fig. 23 Air Mollier Diagram

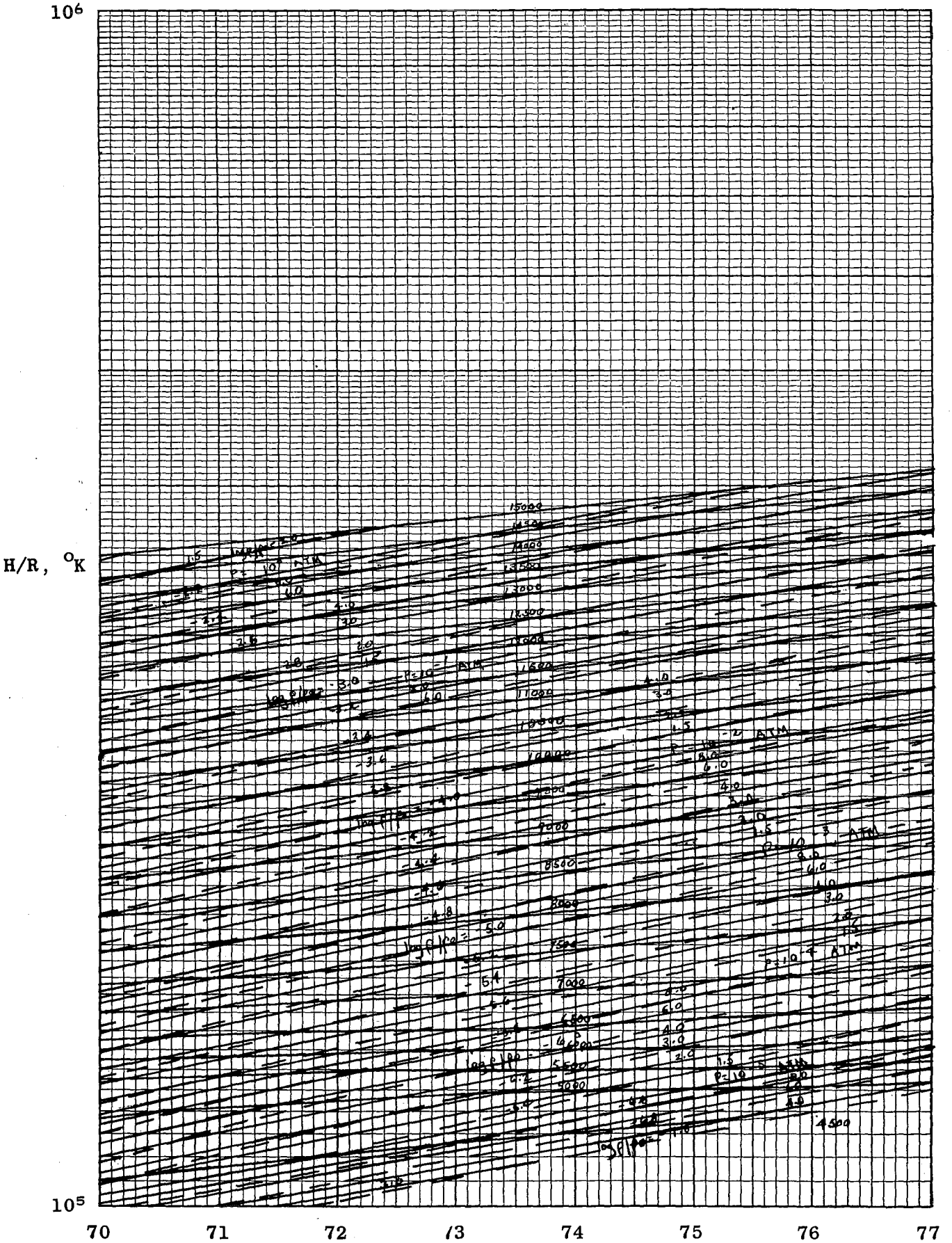



Fig. 24 Air Mollier Diagram

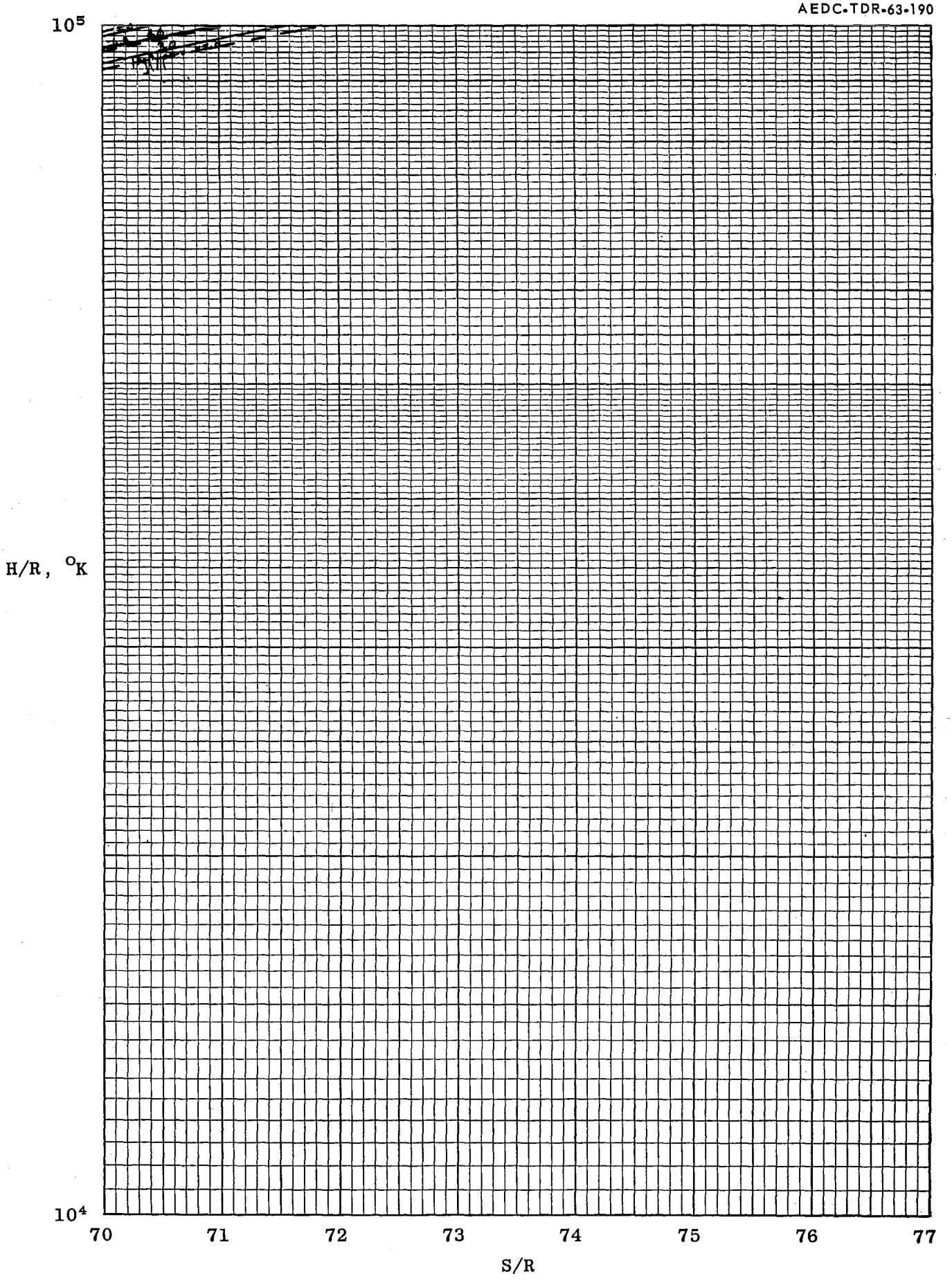



Fig. 25 Air Mollier Diagram

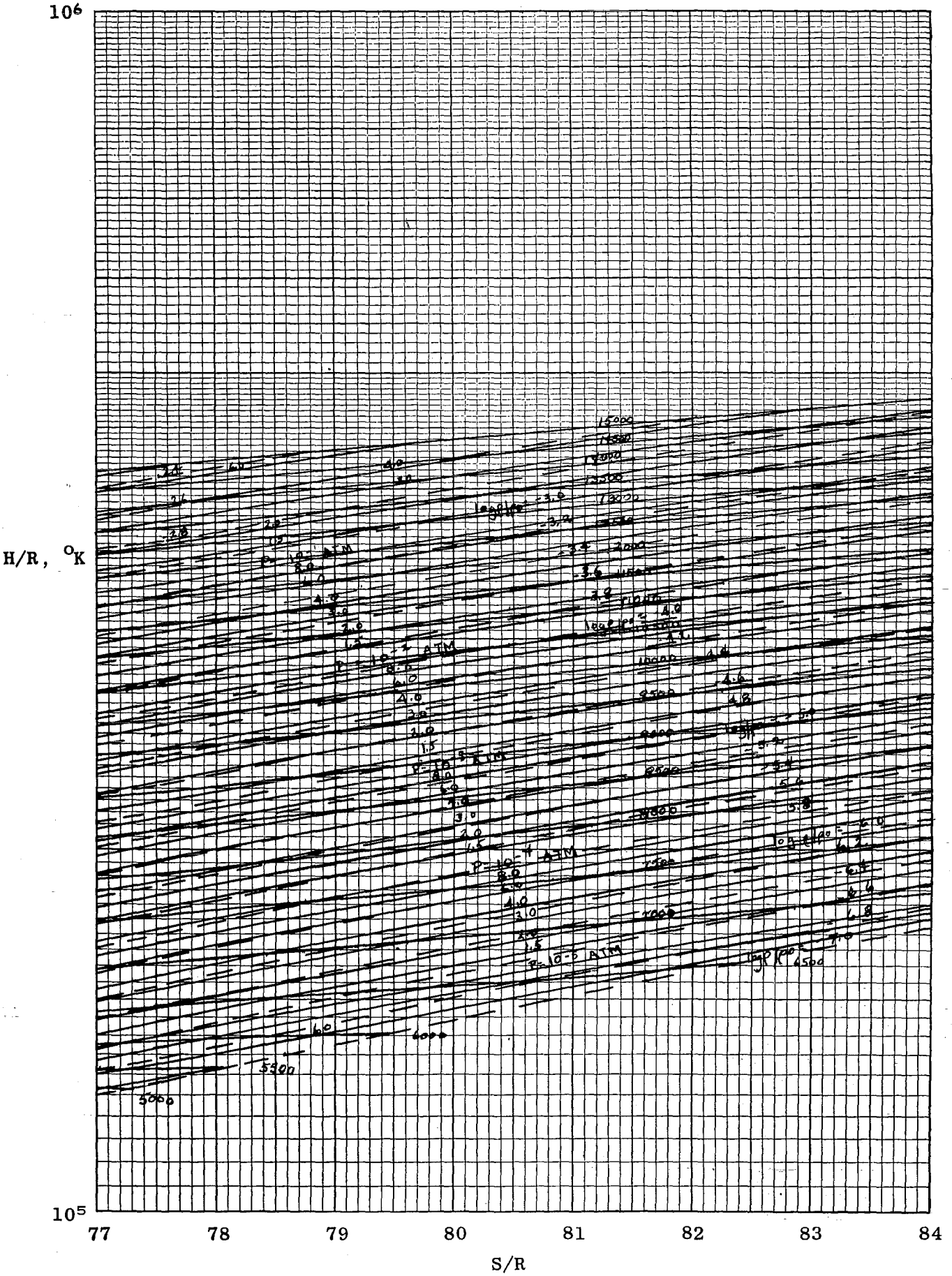



Fig. 26 Air Mollier Diagram

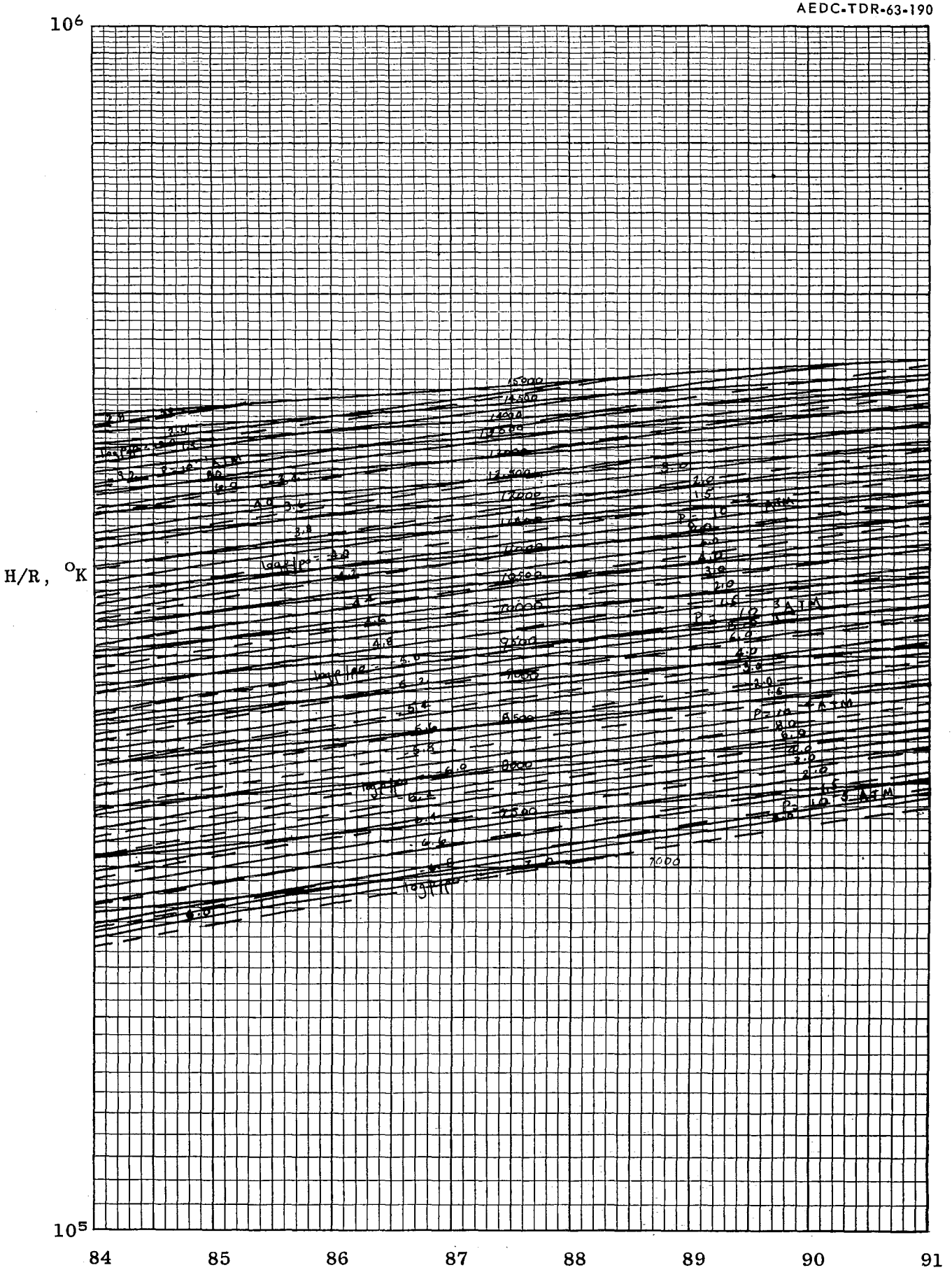



Fig. 27 Air Mollier Diagram

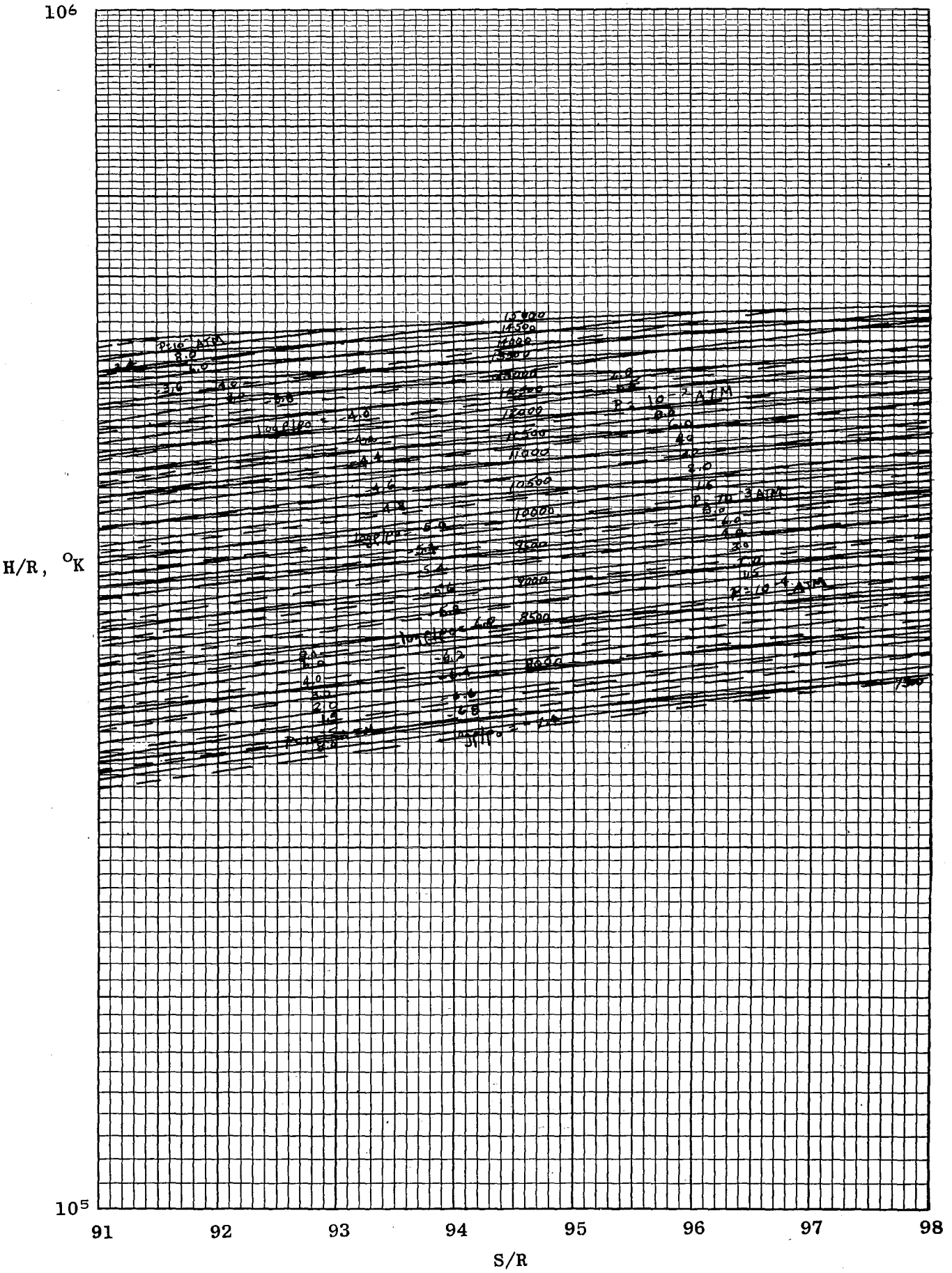



Fig. 28 Air Mollier Diagram

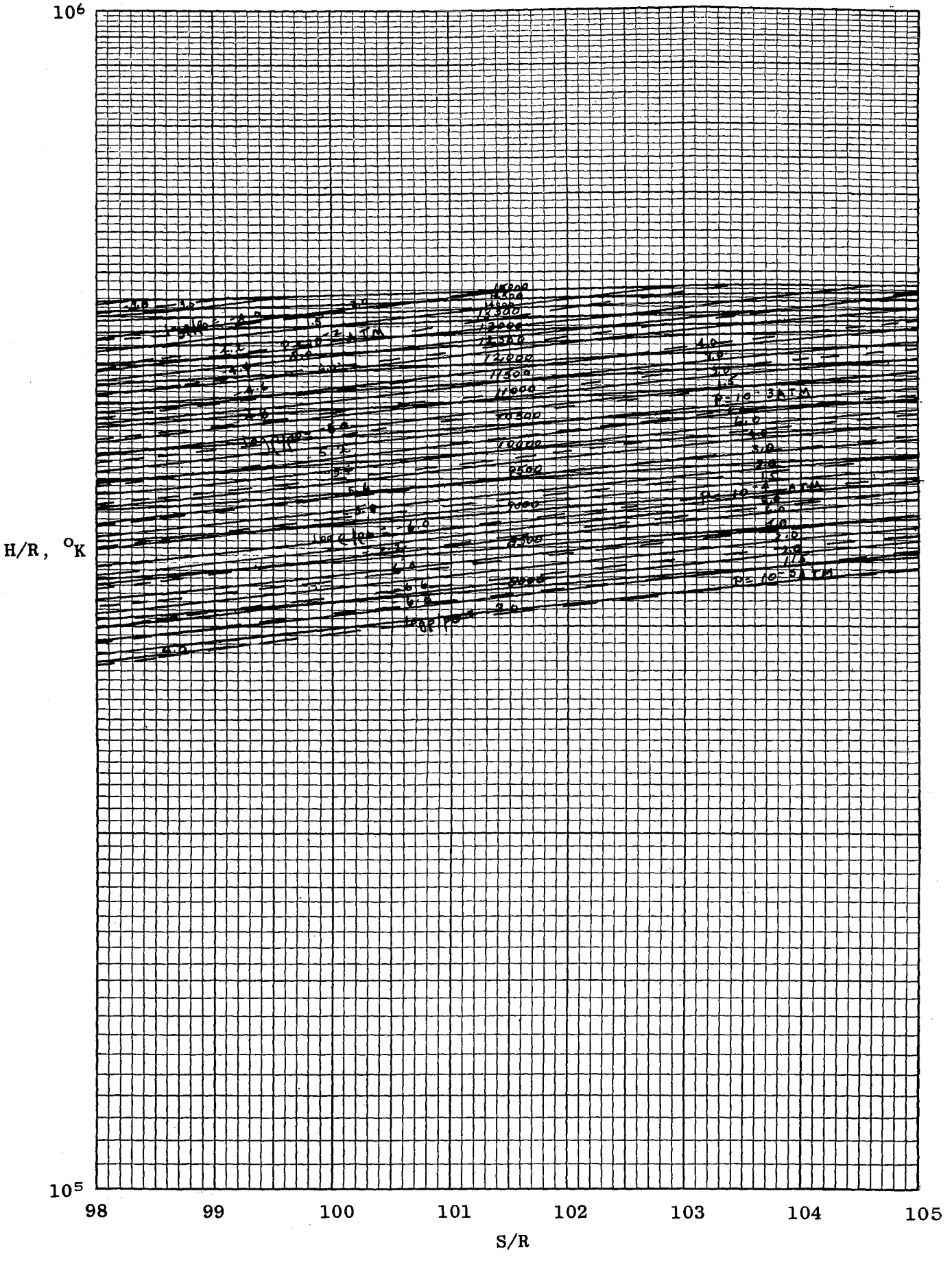



Fig. 29 Air Mollier Diagram

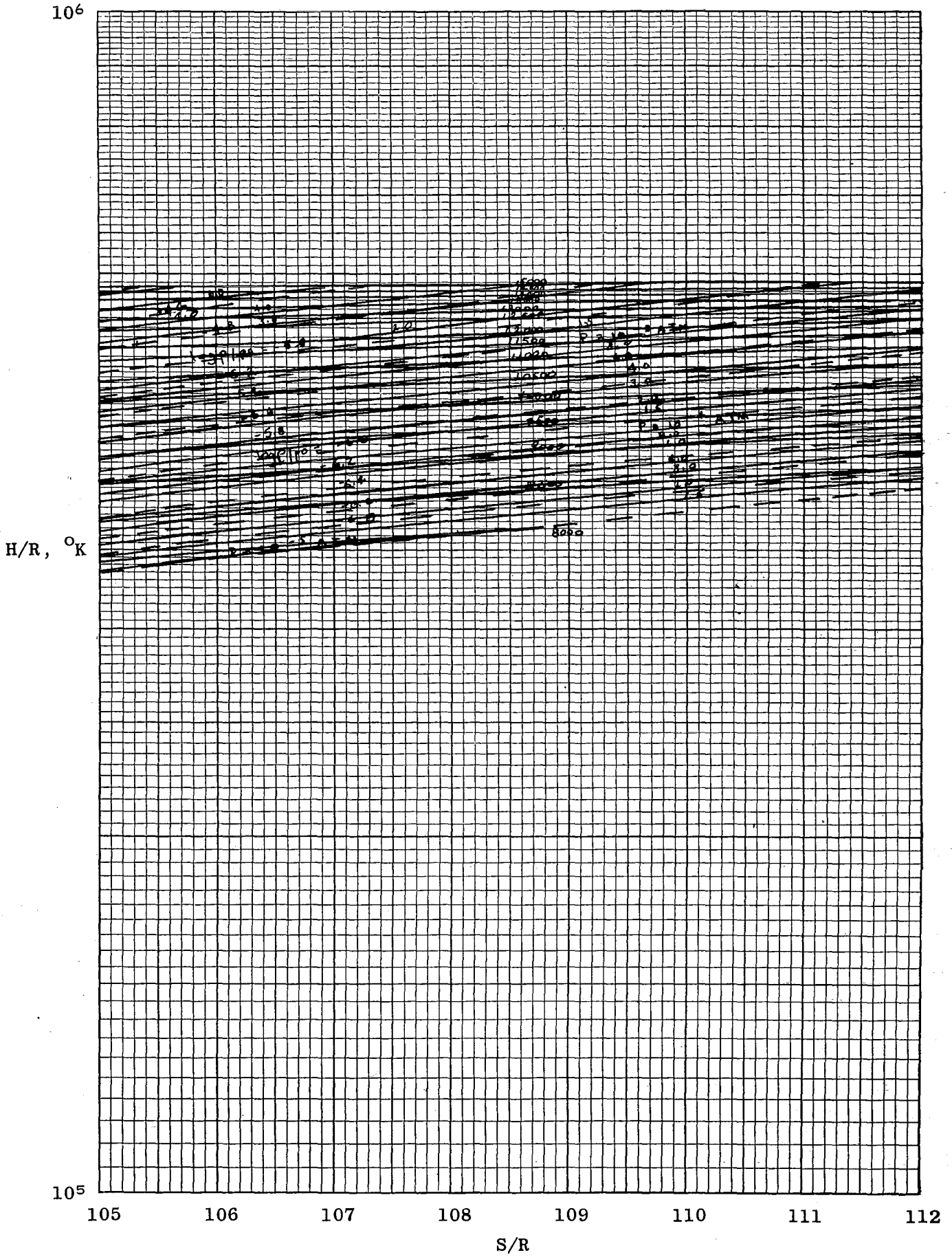



Fig. 30 Air Mollier Diagram

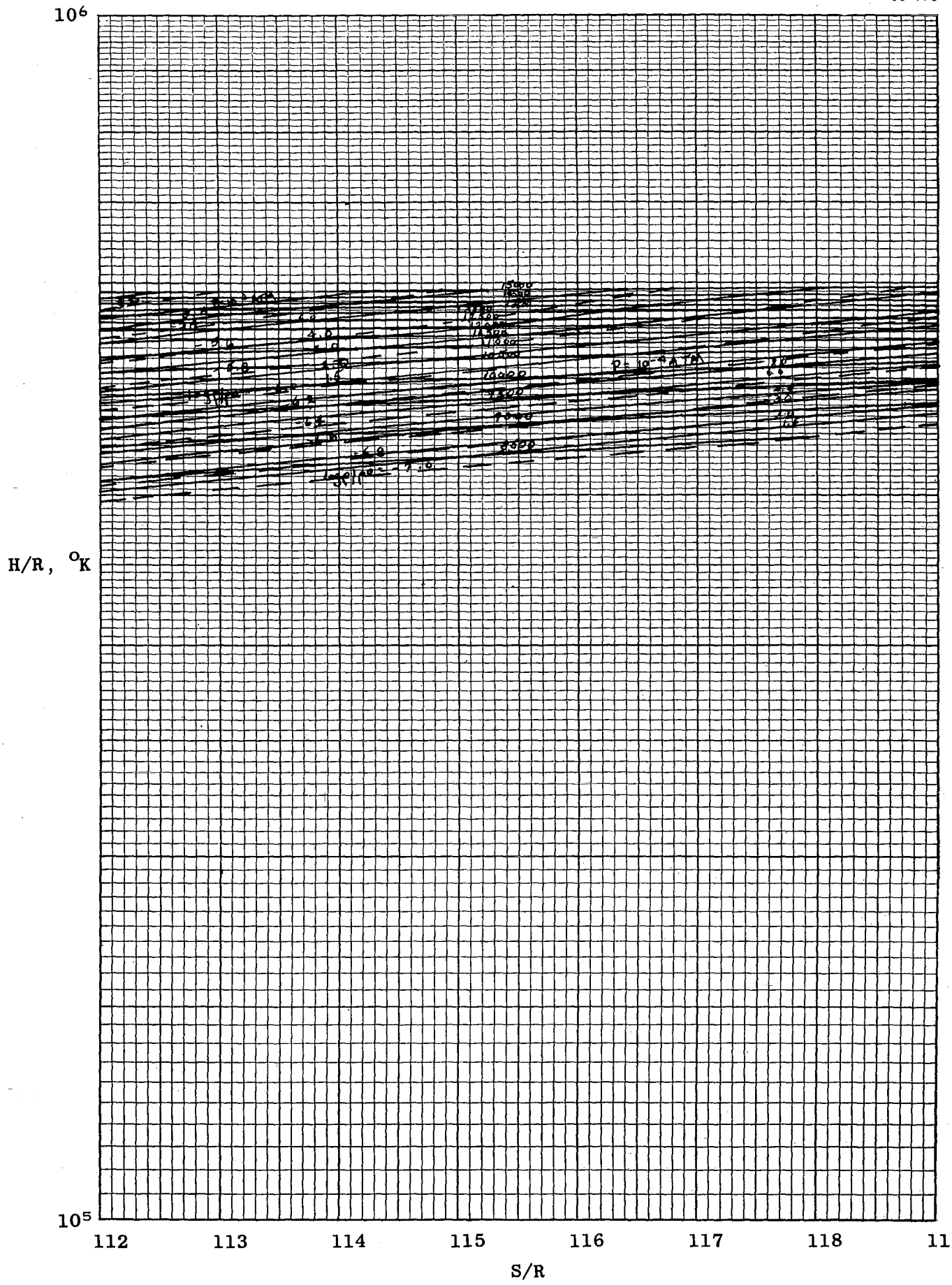



Fig. 31 Air Mollier Diagram

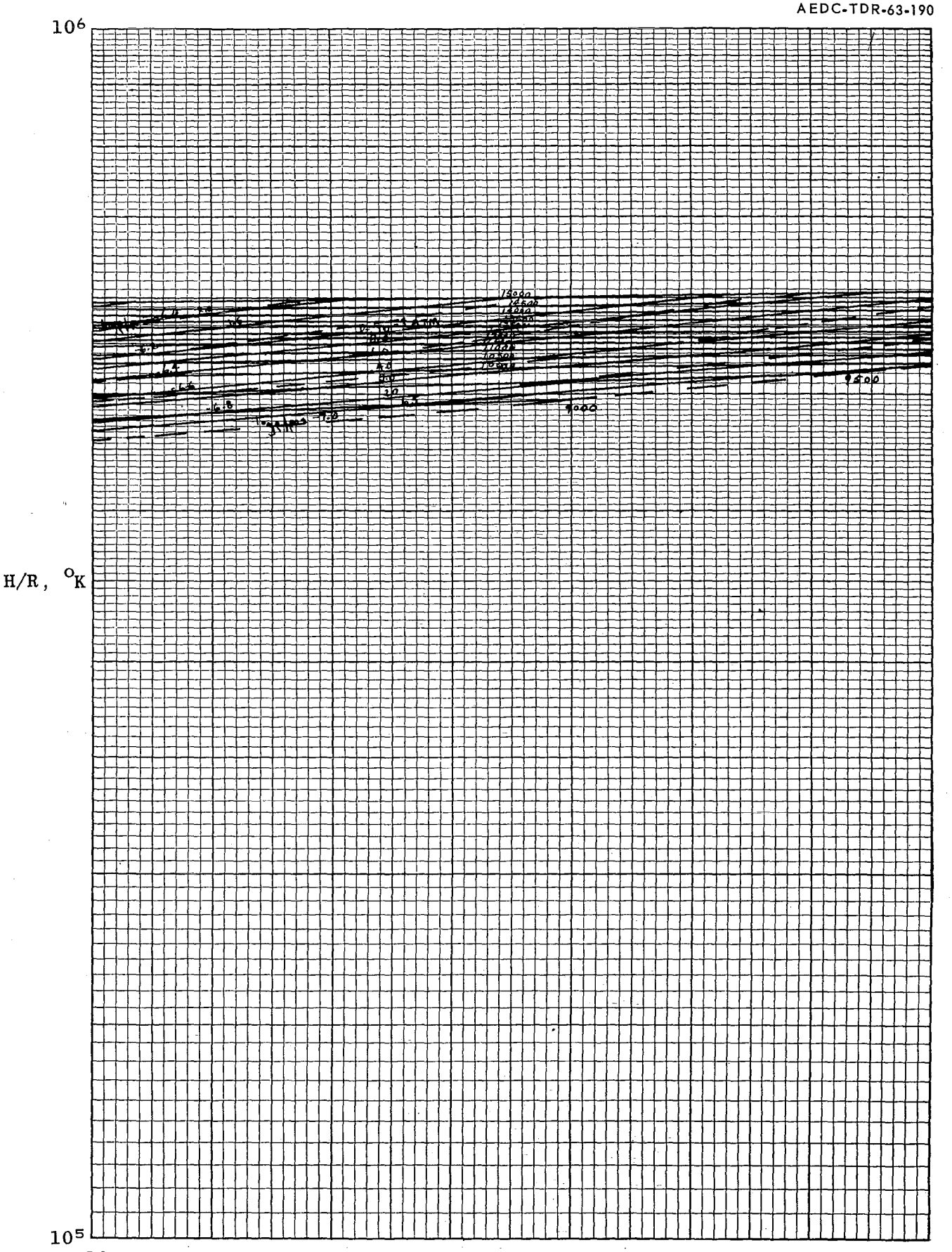



Fig. 32 Air Mollier Diagram

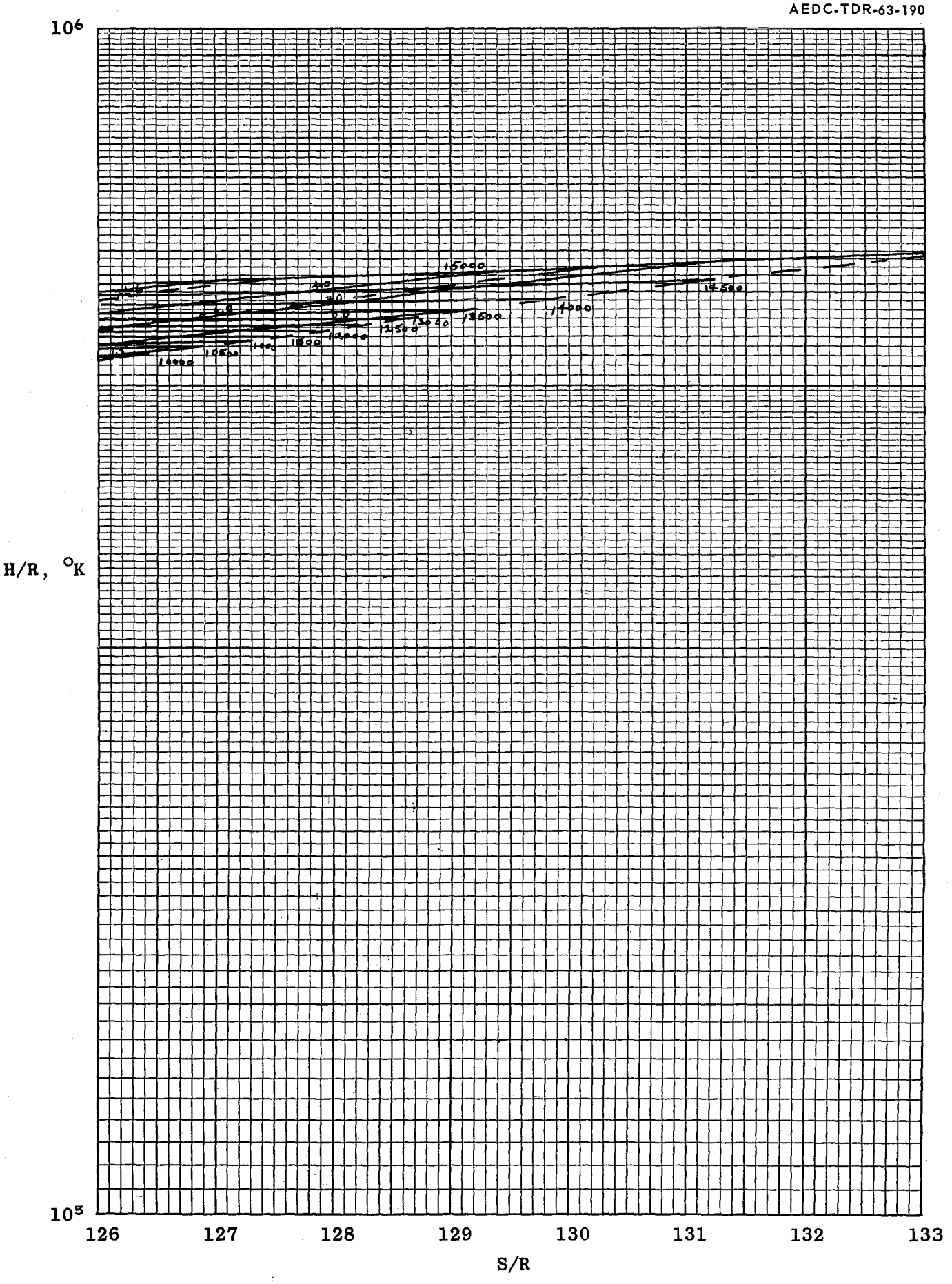



Fig. 33 Air Mollier Diagram